Pre-Conference Workshop

Workshop 8: DOE Buildings Envelope Research Projects

Session Overview

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Outline/Agenda

- 1 – 4 pm:

Session on Advanced Research Projects Agency – Energy (ARPA-E) Programs

- 4 – 5 pm:

Session on Building Technologies Office (BTO) Programs

DOE R&D Strategies

ARPA-E

- Both focused and open programs organized around core areas of:
  - Electricity Generation & Delivery
  - Efficiency
  - Transportation
- No long-term roadmaps identifying specific areas of R&D
- Focus of today's session:
  - Introduce SHIELD program, lessons learned, and key outputs
  - Solicit feedback on next steps post-ARPA-E funding and identify pathways for commercialization

Building Technologies Office

- Organized around four program areas:
  - Emerging Technologies (ET)
  - Residential Buildings Integration
  - Commercial Buildings Integration
  - Codes and Standards
- Areas of interest identified through periodic R&D assessment exercises
- Focus of today's session:
  - Provide a status update on the Windows and Opaque Envelope Research & Development Opportunity (RDO) reports
  - Introduce the BTO Grid-interactive Efficient Buildings (GEB) reports

2019 Buildings XIV International Conference

Pre-Conference Workshop
Workshop 8: DOE Buildings Envelope Research Projects

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arpa·e
CHANGING WHAT'S POSSIBLE

The ARPA-E SHIELD Program – A Window into the Future of Novel Materials for Thermal Management

Acknowledgements

- Today’s presenters
- ARPA-E Team: Brian Borak, Ashok Gidwani, Patrick Finch, Mary Yamada
- SHIELD program performers (past and present)
- Jennifer Gerbi (ARPA-E), Eric Schiff (Syracuse), Graciela Blanchet
- Prior Technical Advisors: Chris Konek, Dan Matuszak, Ziggy Majumdar

Outline/Agenda

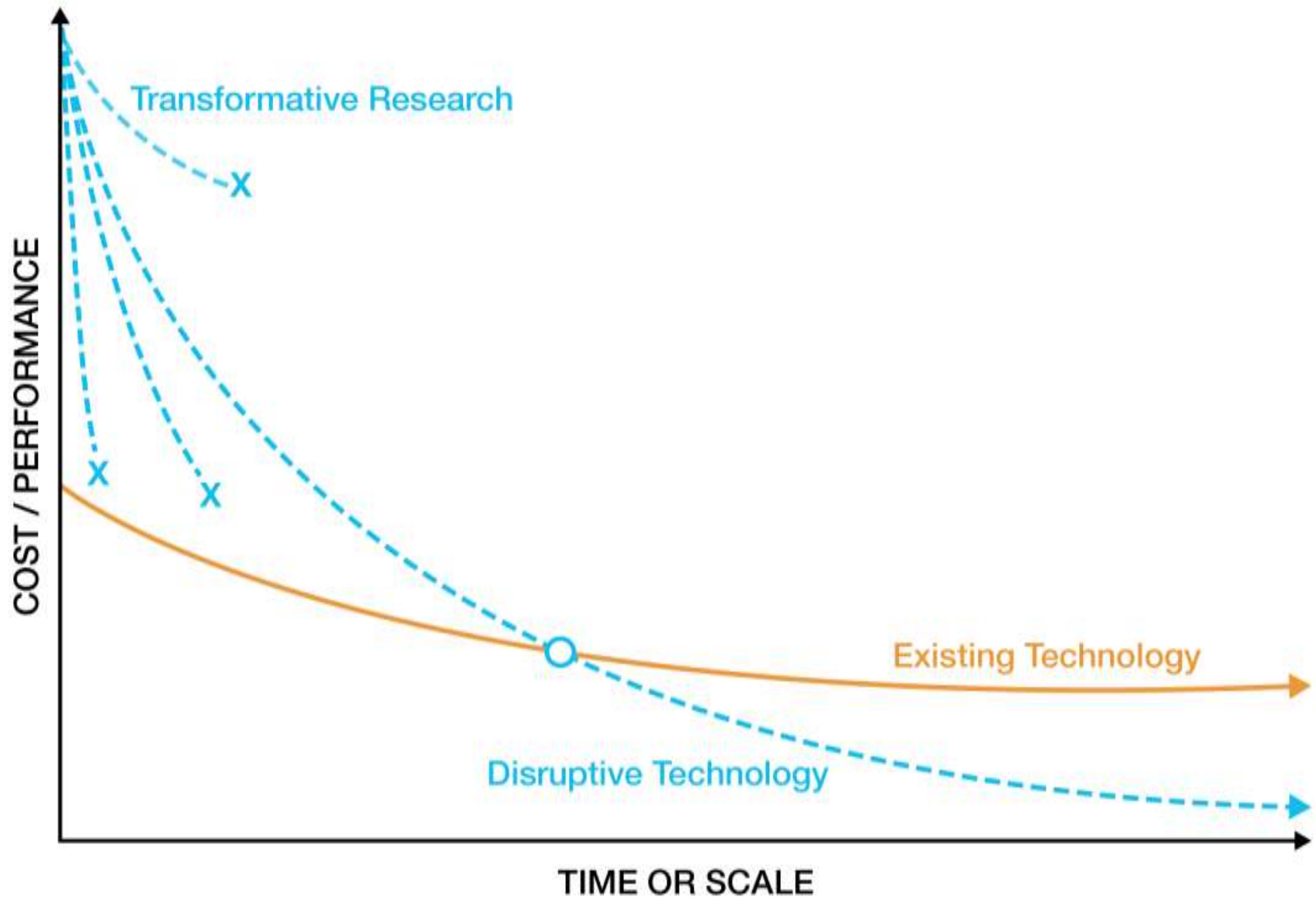
Time	Event
1:00 PM - 1:20 PM	**SHIELD Program Introduction and Retrospective** Dr. Marina Sofos, *ARPA-E*
1:20 PM – 2:50 PM	**SHIELD Team Project Recaps** 1. University of Colorado, Boulder: Prof. Ivan Smalyukh 2. Arizona State University: Dr. Shannon Poges 3. Palo Alto Research Center (PARC): Dr. Mahati Chintapalli 4. Aspen Aerogels: Dr. Wendell Rhine 5. University of California, Los Angeles: Prof. Laurent Pilon
2:50 PM – 3:00 PM	**SHIELD Program Commercialization Pathways** Patrick Finch, *ARPA-E/Booz Allen Hamilton*
3:00 PM – 3:15 PM	**Prospects for SHIELD aerogel technology for the windows market** Dr. George Gould, *Aspen Aerogels*
3:15 PM – 3:30 PM	**SHIELD Technology Durability Testing and Failure Assessment** Dr. Robert Tenent, *National Renewable Energy Laboratory*
3:30 PM – 4:00 PM	**Industry Perspective Presentations, Window product development, first markets and next steps for R&D** Dr. Kayla Natividad, *Pilkington* Dr. Keith Burrows, *Cardinal Glass*

What is ARPA-E?

The Advanced Research Projects Agency-Energy (ARPA-E) is an agency within the U.S. Department of Energy that:

- Provides **Research and Development** funding for high-risk, high-reward, transformational ideas
- Focuses on technologies that could **fundamentally change** the way we get, use and store energy
- Accelerates energy innovations that will create a more secure, affordable, and sustainable **American energy future**

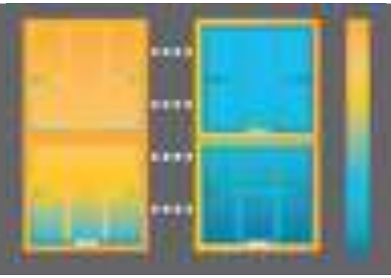
Creating New Learning Curves



Addressing Single-Pane Windows

SHIELD

Single-Pane Highly Insulating Efficient Lucid Designs



Mission

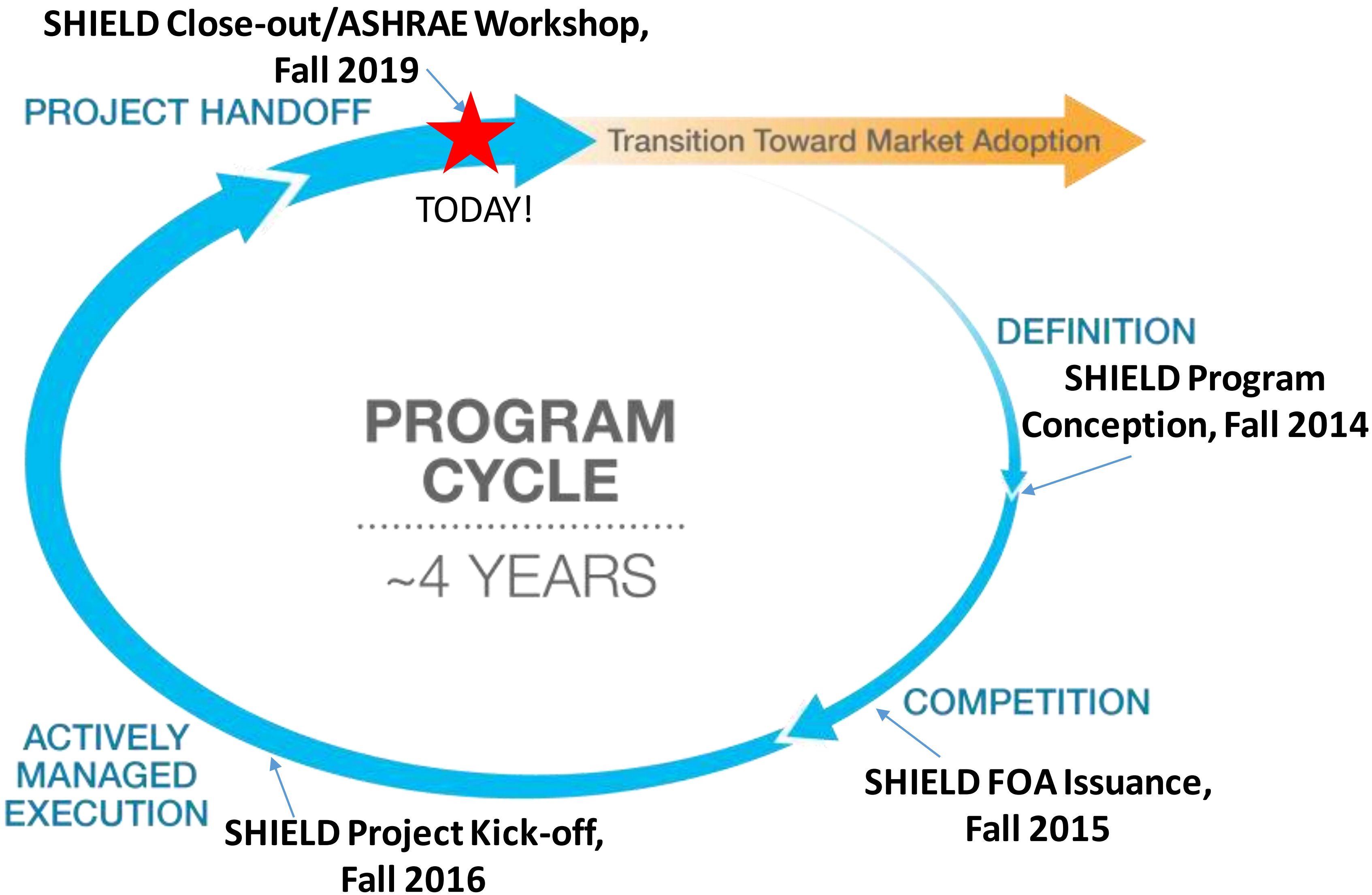
- Develop innovative materials that will improve the energy efficiency of existing single-pane windows in commercial and residential buildings.

Year	2016
Projects	14
Funding Amount	$30.9 million

Goals

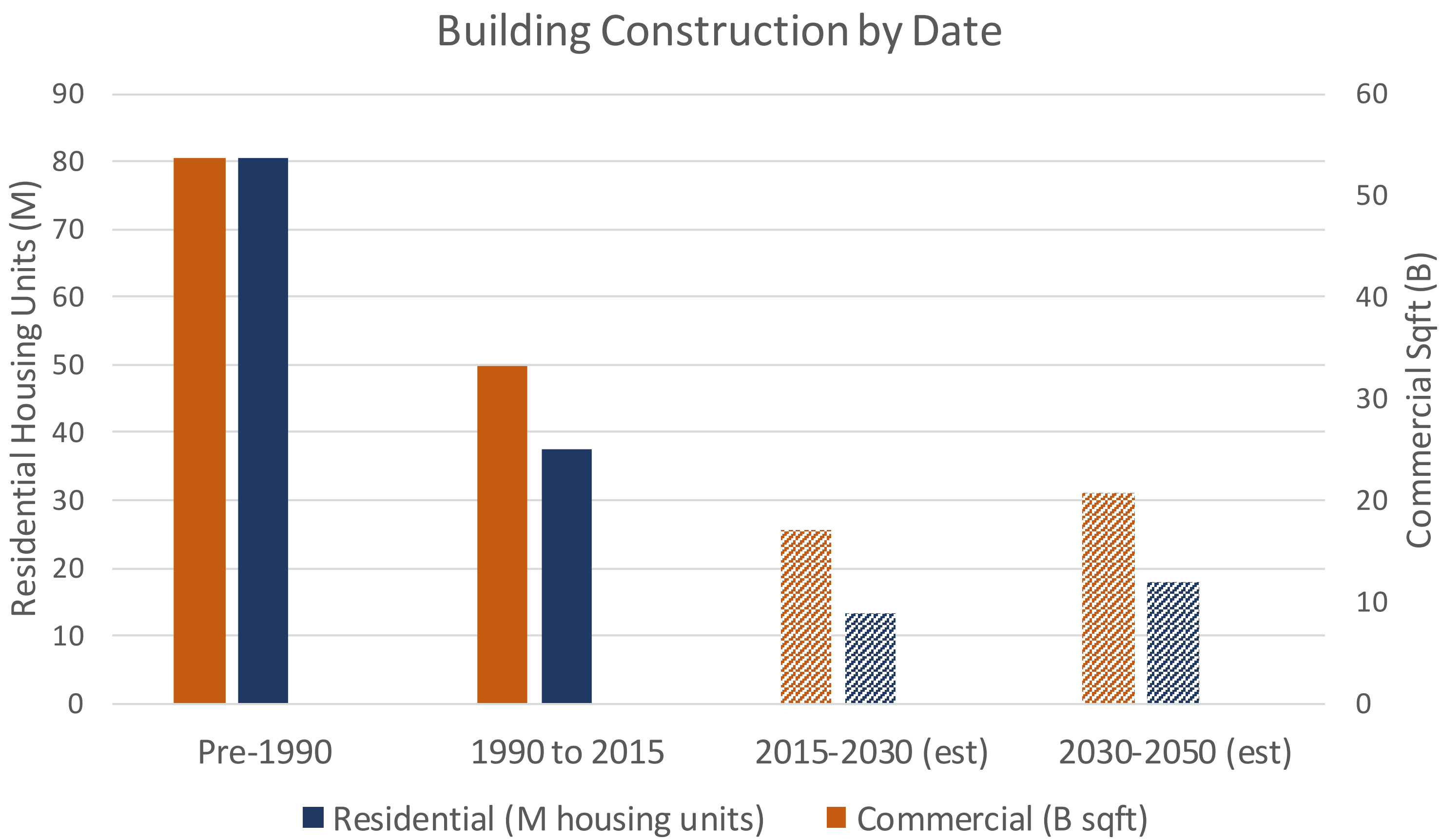
- Develop technologies in three technical categories:
    1. Products that can be applied onto existing windowpanes
    2. Manufactured windowpanes that can be installed into the existing window sash
    3. Other early-stage, highly innovative technologies that can enable products in the first two technical categories
- Cut in half the amount of heat lost through single-pane windows. These materials would improve insulation, reduce cold weather condensation, and enhance occupant comfort
- Produce secondary benefits, such as improved soundproofing, that will make retrofits more desirable to building occupants and owners

Technology Acceleration Model



New Construction Rate is Limited…

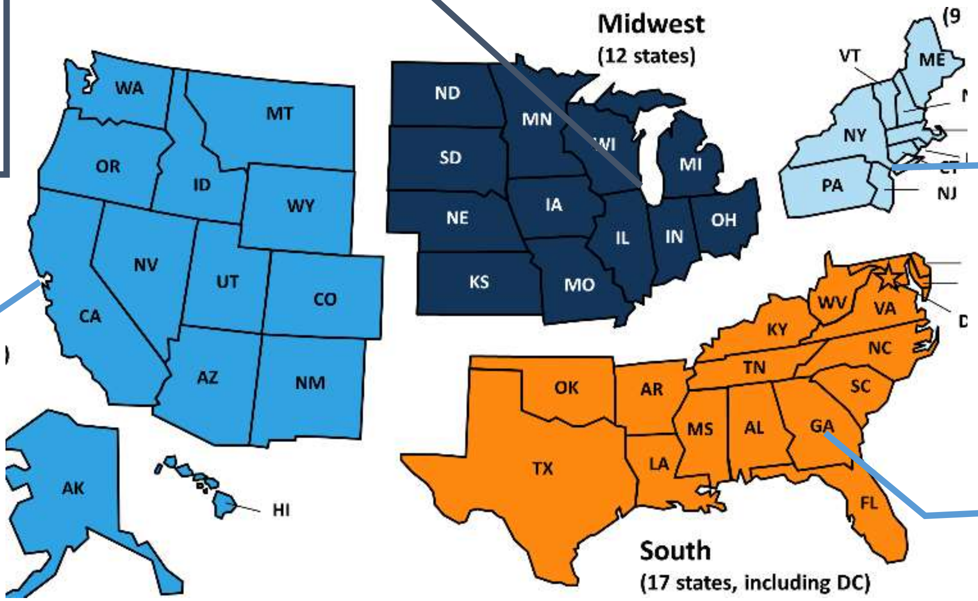
leaving a significant retrofit opportunity



Size of Single Pane Retrofit Market

2.9B ft^2

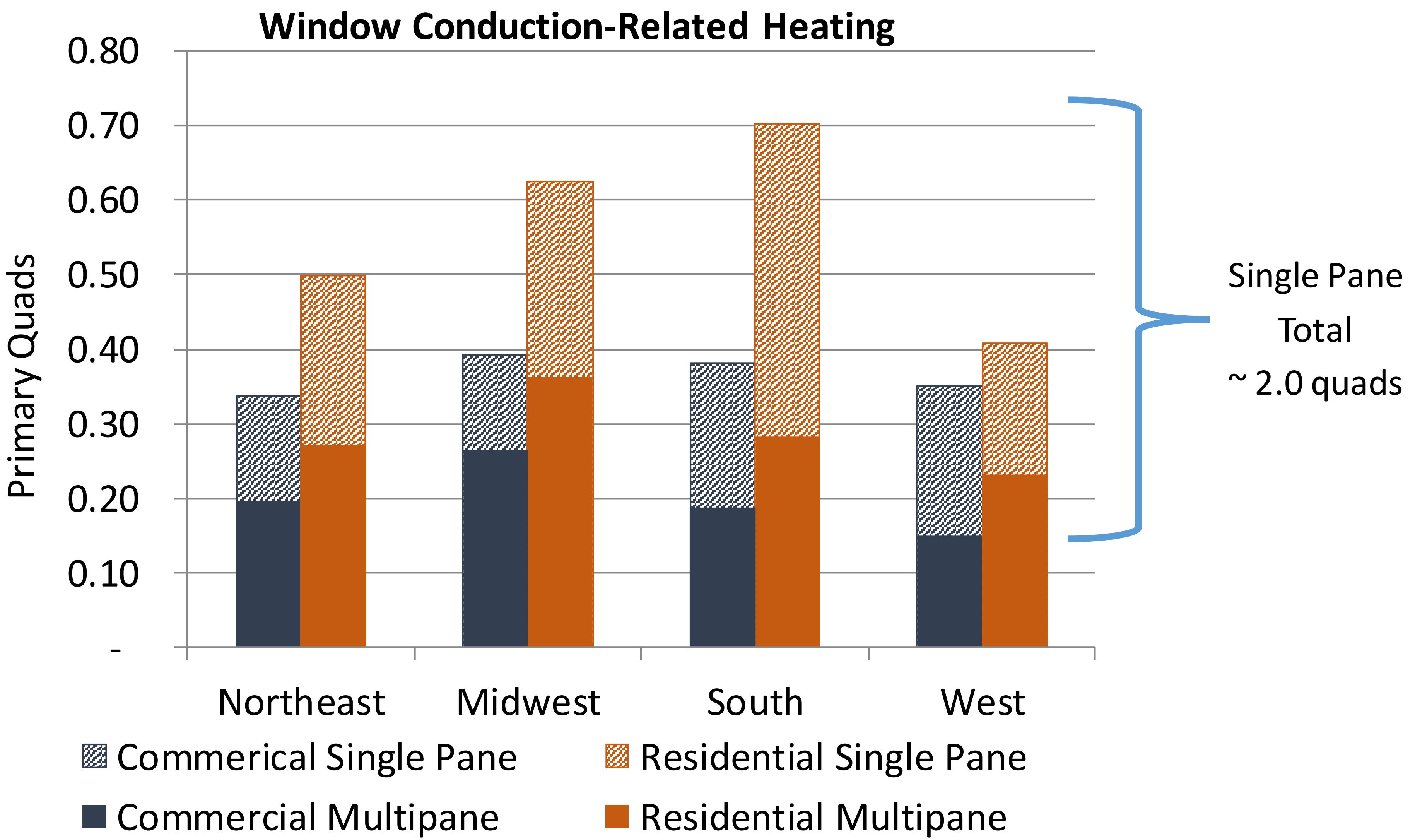
2.5B ft^2



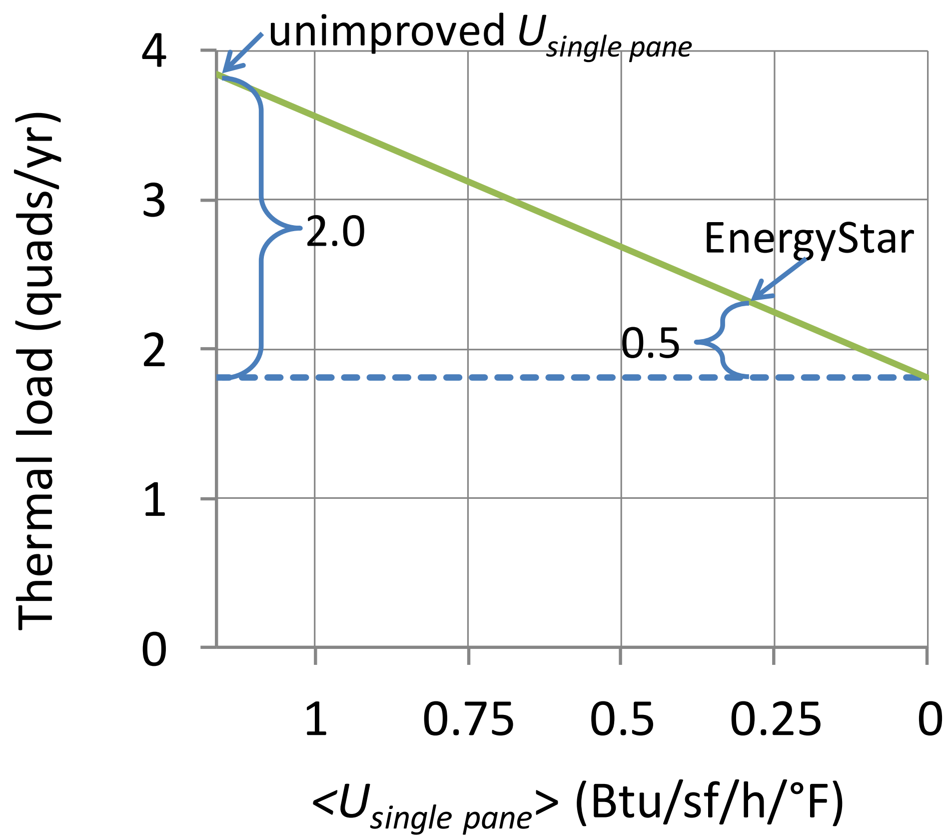
3.0B ft^2

7.2B ft^2

Heating Loads from Window Conduction



Improving $U_{single\text{-}pane}$ reduces heating costs



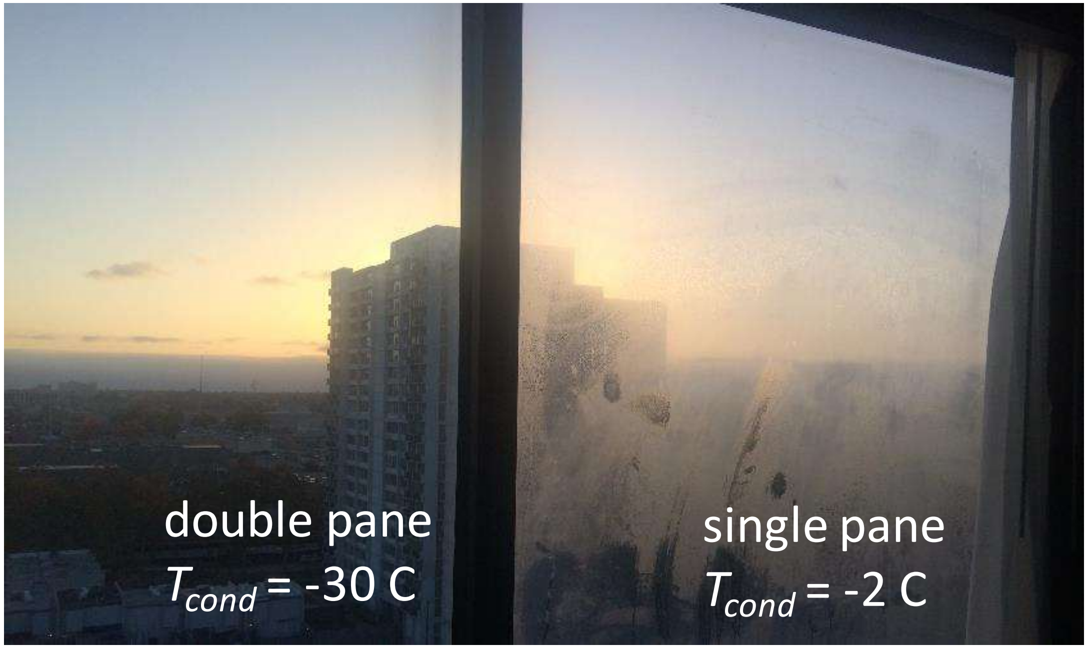
Why do single pane windows persist?

Within the existing building stock (i.e. retrofits):

- IGU lifetimes are typically 15-30 years
- Rate of return on retrofit investments is typically less than 0%
- Failures in IGU installations
- Weight restrictions for some existing construction
- Architectural restrictions for historical building types

Additional Obstruction of Clarity…

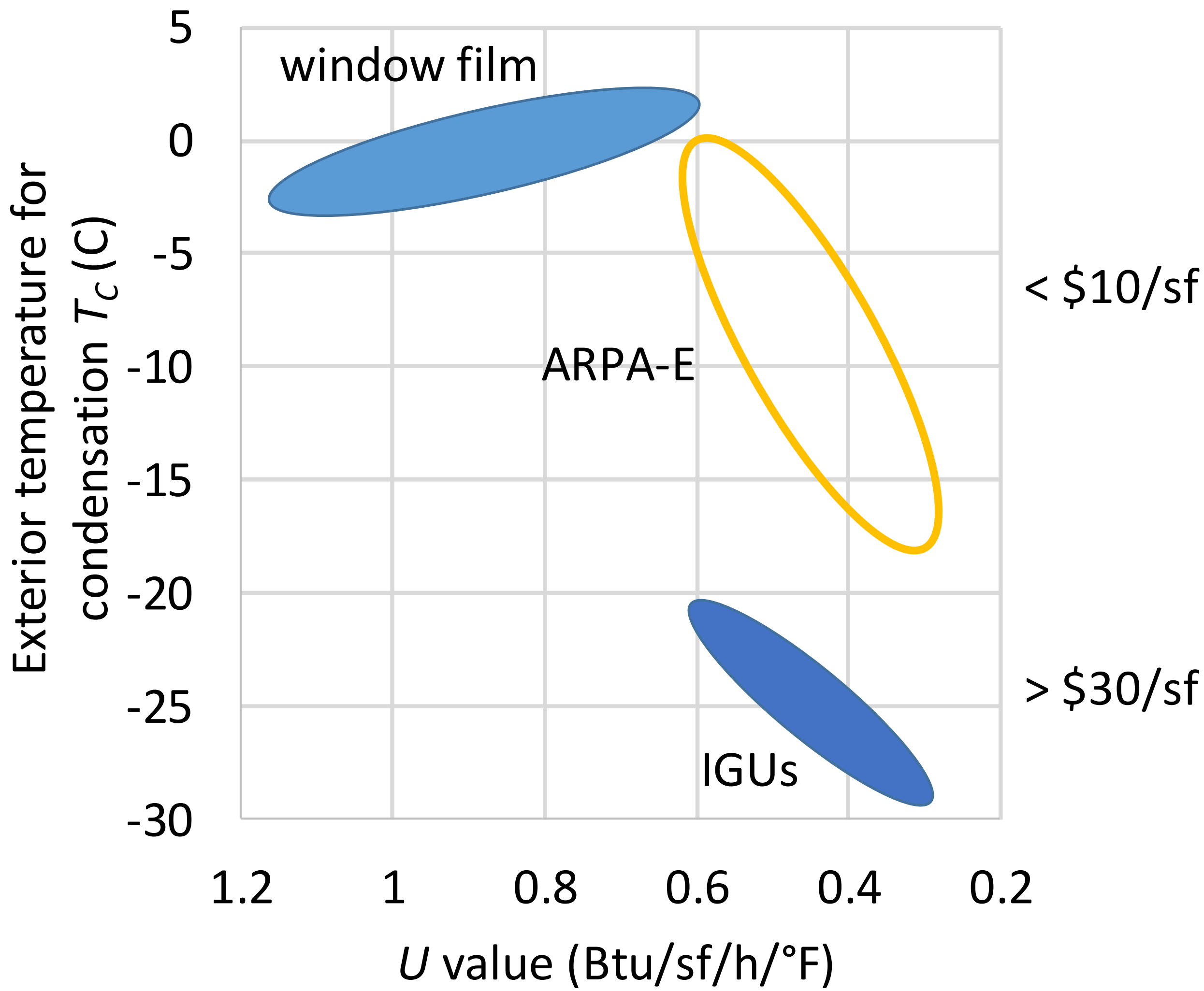
condensation resistance



Interior air at 21 C & 30% relative humidity

- Not only unsightly, condensation undoes the *U* improvement from low-e films
- Condensation precludes a healthful indoor humidity

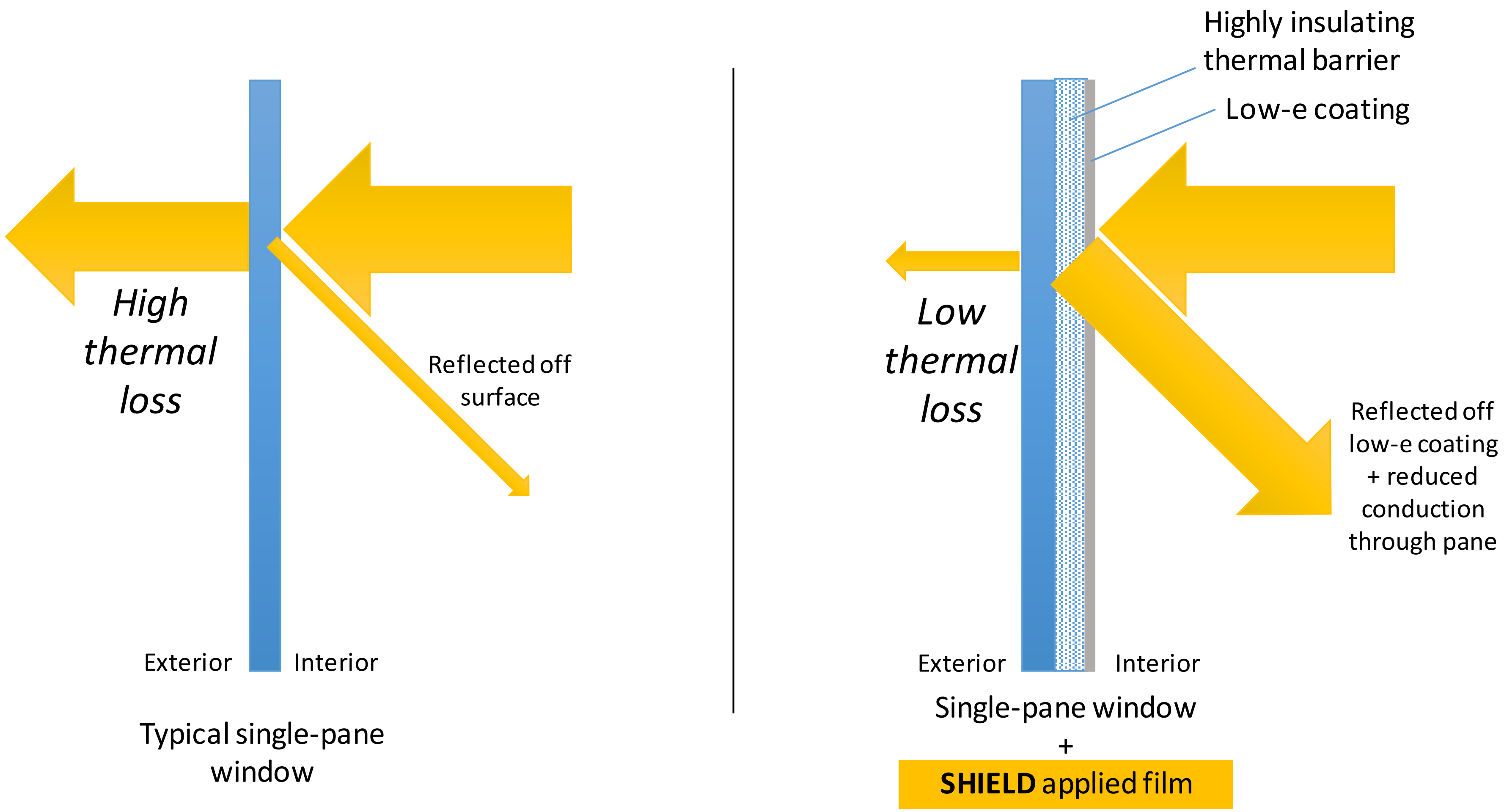
ARPA-E White Space



Condensation: 3 C dewpoint, T_{in} = 21 C, v_{wind} = 15 mph

Program Concept

- Significantly reduce <u>cold-weather</u> thermal losses through single-pane windows via new applied films or replacement panes



Further Defining the White Space for Innovation

- **Novel materials** may be able to reduce energy loss, while maintaining occupant comfort
- **Thermal conductivities, sample sizes, and mechanical stabilities** are not sufficient for cost-effective windows energy saving solutions
- **Material pore size and size distribution** difficult to control to reduce haze and maximize visible light transmission (Tvis) on a scale that is relevant to window applications
- **Rapid fabrication techniques** must be compatible with established insulating glass and window manufacturing processes

SHIELD Program Metrics

- **CATEGORY 1: Applied Product Targets**

ID	Property	Metric
1.1	winter U-factor (center-of-glass)	less than 0.50 BTU/sf/hr/°F
1.2	exterior temperature for interior condensation (center-of-glass)	less than -5 C
1.3	exterior temperature at which the interior pane surface has radiative temperature 11 C (center-of-glass)	less than 0 C
1.4	haze	less than 2%
1.5	visible transmittance	more than 70%, with a color rendering index R_a > 0.9 .
1.6	estimated manufacturing cost	less than $5 per square foot
1.7	estimated median service lifetime	more than 10 years

- **CATEGORY 2: Manufactured Pane Targets**

ID	Property	Metric
2.1	winter U-factor (center-of-glass)	less than 0.40 BTU/sf/hr/°F
2.2	exterior temperature for interior condensation (center-of-glass)	less than -10 C
2.3	exterior temperature at which the interior pane surface has radiative temperature 11 C (center-of-glass)	less than -5 C
2.4	haze	less than 1%
2.5	visible transmittance	more than 80%, with a color rendering index R_a > 0.9 .
2.6	estimated manufacturing cost	less than $10 per square foot
2.7	estimated median service lifetime	more than 20 years

(CATEGORY 3: Partial Solutions)

Original SHIELD Portfolio Break-down

Category 1: Applied Products

Products that adhere to an existing windowpane

- **University of Colorado, Boulder**
- **SRI International**
- **IRDynamics**
- **nanoSD**
- **University of California, San Diego**

Category 2: Manufactured Panes

Manufactured windowpanes that can be installed in existing sashes

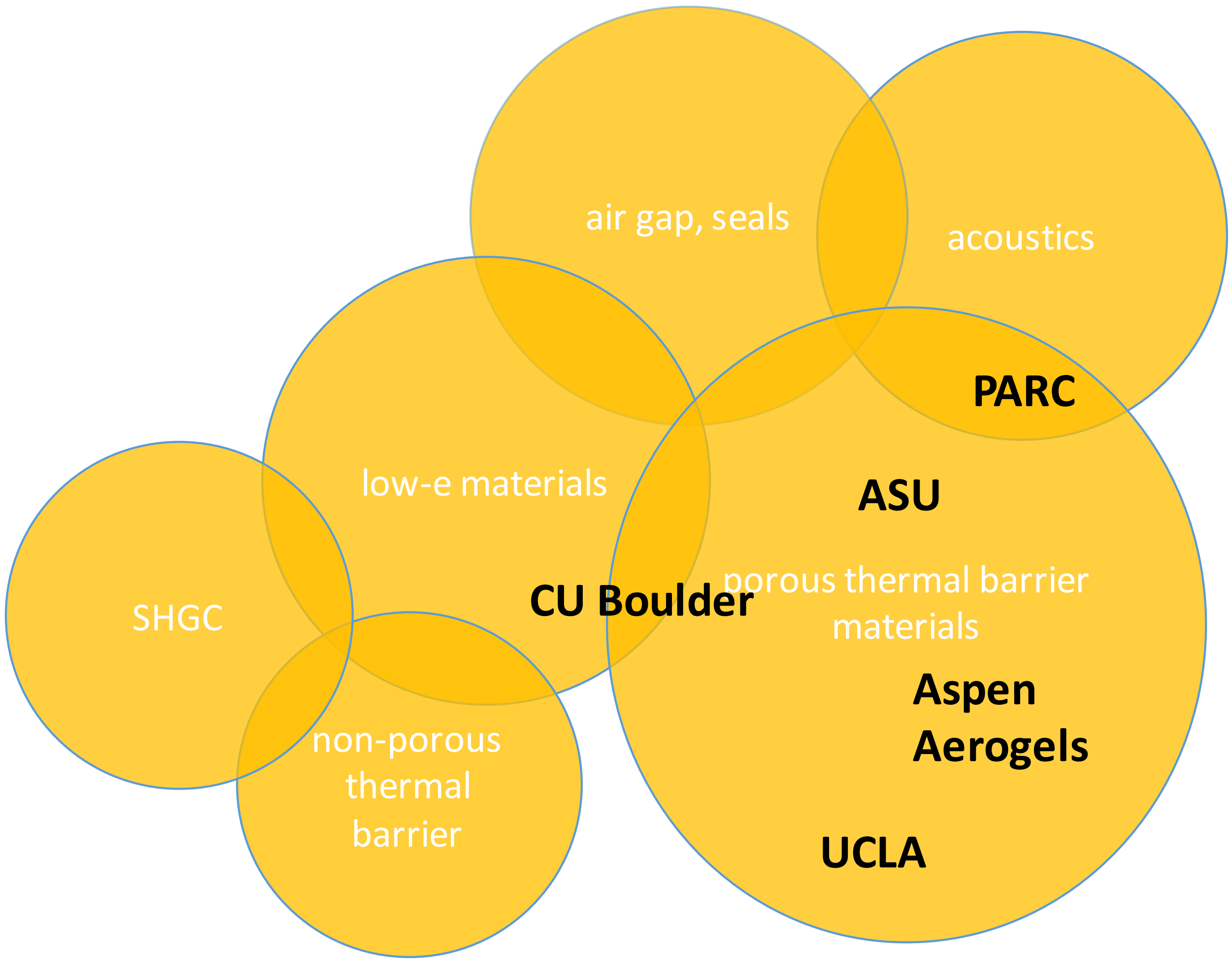
- **Aspen Aerogels**
- **Arizona State University**
- **Triton Systems, Inc.**
- **Palo Alto Research Center (PARC)**

Category 3: Innovative Partial Solutions

Components that enable Category 1 or 2 technologies

- **University of California, Los Angeles**
- **Virginia Commonwealth University**
- **Argonne National Laboratory**
- **Eclipse Energy Systems, Inc.**

Current SHIELD Technology Portfolio



- Porous materials = aerogels (silica, silica/polymer, polymer, cellulose), plasma spray silica, nanofoams.
- Non-porous materials = polymer+ composites.

How Far Have We Come?

- Porous silica-containing films with smaller pore sizes (<100 nm) have been demonstrated at ~3 mm thickness, driving down haze and increasing T_{vis}
- Crack-free (monolithic) and uniform films produced up to 1 m^2 scale, though with long fabrication times (several days)
- Porous polymer films show promise, but have not yet achieved the level of performance of silica-containing films

Metric	PROGRAM TARGET	Achieved To-Date
Size	> 1 ft^2 (notionally)	up to 1 m^2
Haze	<2%	Down to <3 %
Tvis	>70%	Up to 95%
CRI	>90	Up to 95
Uniformity	Visually uniform	Visually uniform
Tk (W/m·K)	(not specified)	Down to 0.01
U (BTU/ft^2/F/hr)	<0.5	Down to 0.4
Calculated Manufacturing Cost	<$5/$ft^2$	Down to $2.45/sqft
Estimated median service lifetime	>10 years	?

Conclusions

Lessons Learned:

- **Optically-clear aerogels** are achievable through various approaches (i.e. silica based aerogels and porous polymers were generally more successful than non-porous materials)
- **Retrofit panes and aerogel-integrated IGUs** appear closer to market than applied films – some durability issues can be mitigated with appropriate edge seals
- **Existing low-e films** (in some cases) can be levered for improving aerogel insulating performance
- **Acoustic attenuation** may be possible with some systems, but looks unlikely or very limited with most porous aerogels

Conclusions

- **Challenges:**
  - Reliable replication of high-performing samples (i.e. yield)
  - Mechanical robustness over time
  - Process improvement to reduce fabrication time (several days -> several hours)
  - Integration into window assemblies
  - Translation to production-environment-compatible processes
  - Improve U-value: now at ~0.5; can this be driven down further at minimal cost?
  - Production cost comparable to (or better than) high performance windows
  - Real-world “in-field” validation of performance

- **Next Steps:**
  - Aerogel IG scale-up, production testing
  - Durability assessment (i.e. in-lab accelerated lifetime testing, in-field performance/failure testing and identification)
  - Engagement with certification bodies (e.g., IGMA, NFRC)
  - Continued Industry engagement

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J.L. Wright, ARPA-E "Single-Pane Window Efficiency Workshop", 2014

Kaiser Family Foundation

QUESTIONS?

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Workshop 8: DOE Building Envelope Research Projects on Fenestration and Grid Interaction

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University of Colorado
Boulder

Super-transparent thermal insulation for boosting window efficiency

Acknowledgements

- **P.I. Smalyukh, CU-Boulder – AIR FILM research & development**
- **Robert Tenent, NREL – product lifetime & durability testing**
- **Vlad Cherpak & Tom Culp, iFeather – pilot line scaling & T2M**

CU Team: Eldho Abraham, Joshua De La Cruz, Blaise Fleury, Bohdan Senyuk, Jan Bart ten Hove, Taewoo Lee, Vlad Cherpak, Trevor Stanley, Steven Morrison, Andrew Hess & Ivan I. Smalyukh

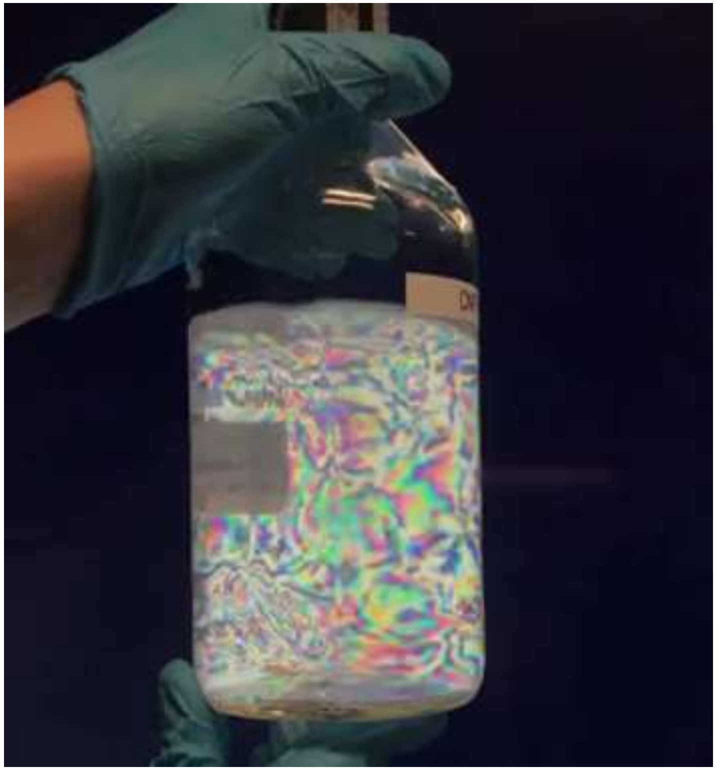
NREL internship

Undergraduate, on UROP fellowship

Undergraduate, on SPUR fellowship

Windows & energy: not a simple problem

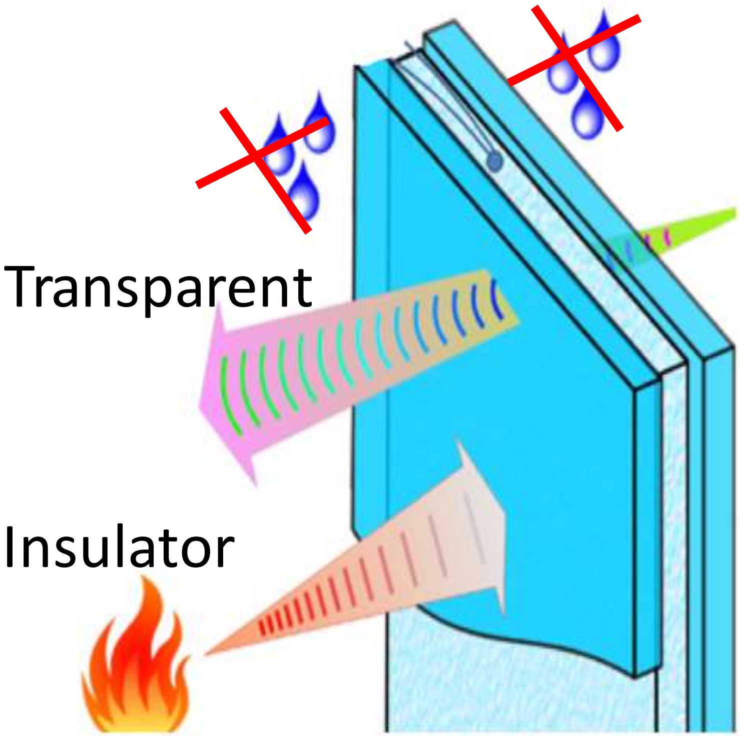
Problem & liquid crystal enabled solution



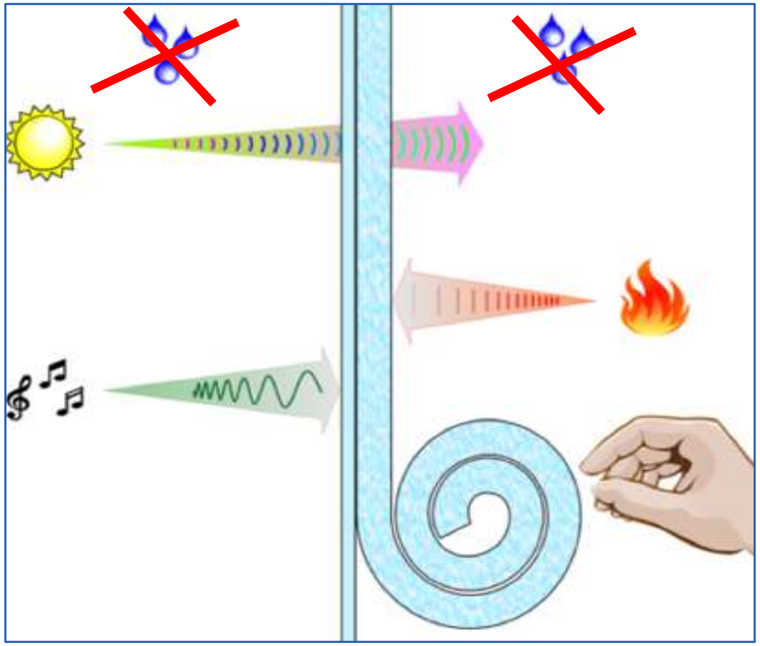
- →**Buildings account for ~15% of global energy consumption**
- →**20% building energy is lost through windows**
- →**About 40% single pane windows**
- →**Need a visibly transparent thermal barrier & low-e**

Transparent aerogels as window products

New breeds of >R5 thin IGUs



Window retrofits



Easy to install!

→**Building wall grade energy efficiency**

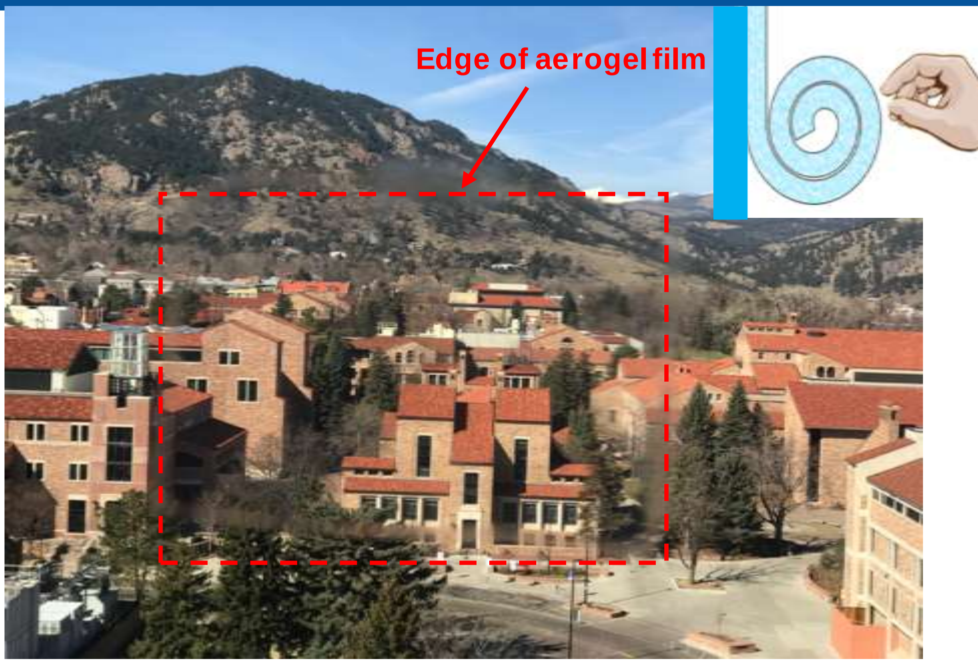
→**Uncompromised transparency**

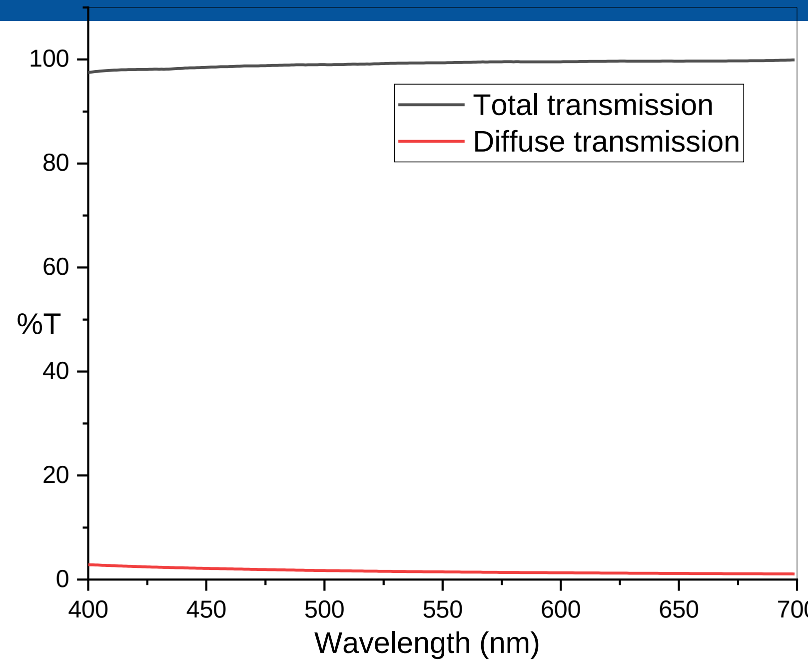
→**Condensation resistance, soundproofing…**

Target metrics for different products

Parameter	Installed product 7-25mm thick IGUs	Retrofit product 1.5-4mm thick film
Transparency	>95% aerogel	>99.5% aerogel
Haze	<1% aerogel	<2% aerogel
Flexibility, robustness	+	+++
U-value, BTU/sf/F/hr	0.1-0.3	<0.35
Color rendering index	>99%	>99%
Cost per square foot	2-3 USD	<1.5 USD
UV & 80/80 tests	<1%relative change	<2%relative change
Product lifetime	30 years	20 years

AIR FILM: “Frozen air” aerogel metamaterial





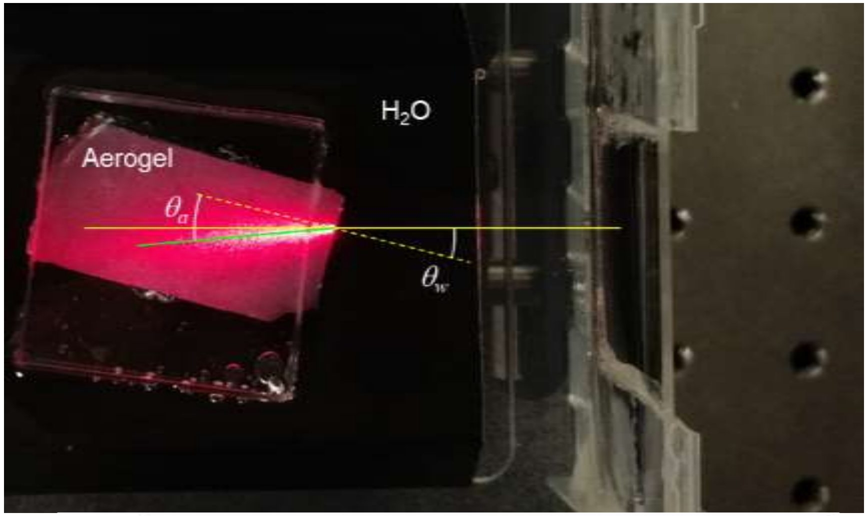
Optically closest to air

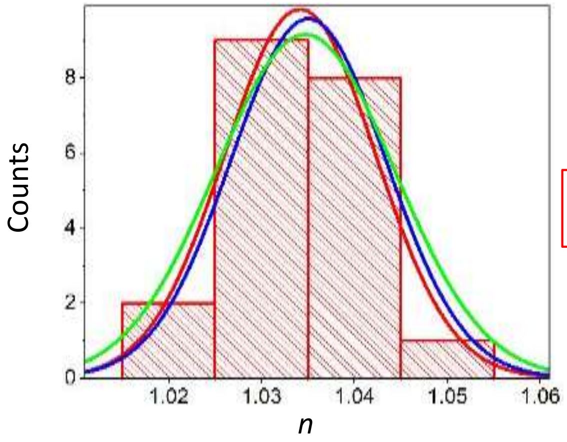
- →**Transmission (glass~92%): >99.**
- →**Haze: ~1% or even less**
- →**Color rendering index: >99%**
- →**Effective refractive index: 1.034**

Refractive index of LC aerogel films

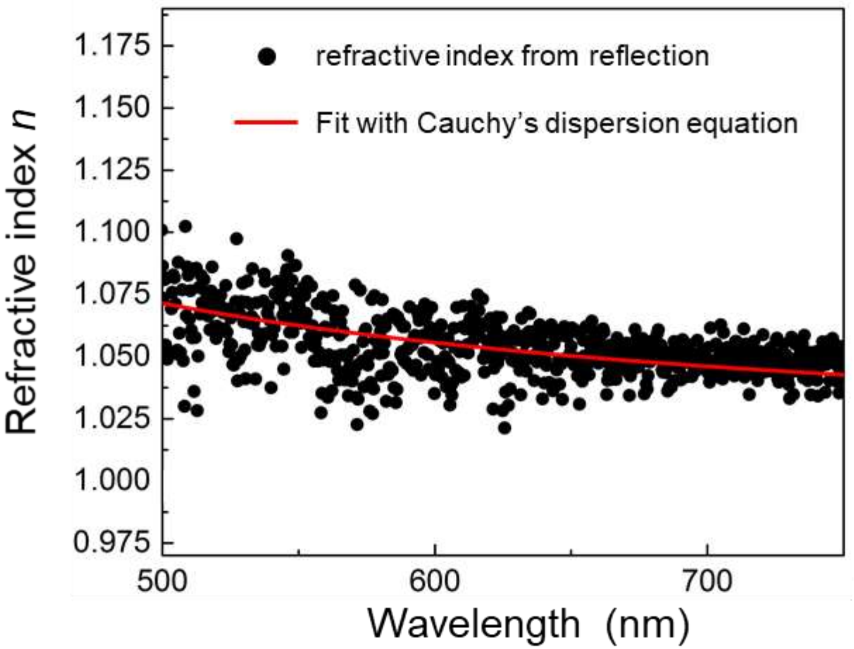
Methods to measure refractive index:

- Snell's Law (see the picture)
- Deviation of a beam by a prism
- Reflection and Fresnel equations





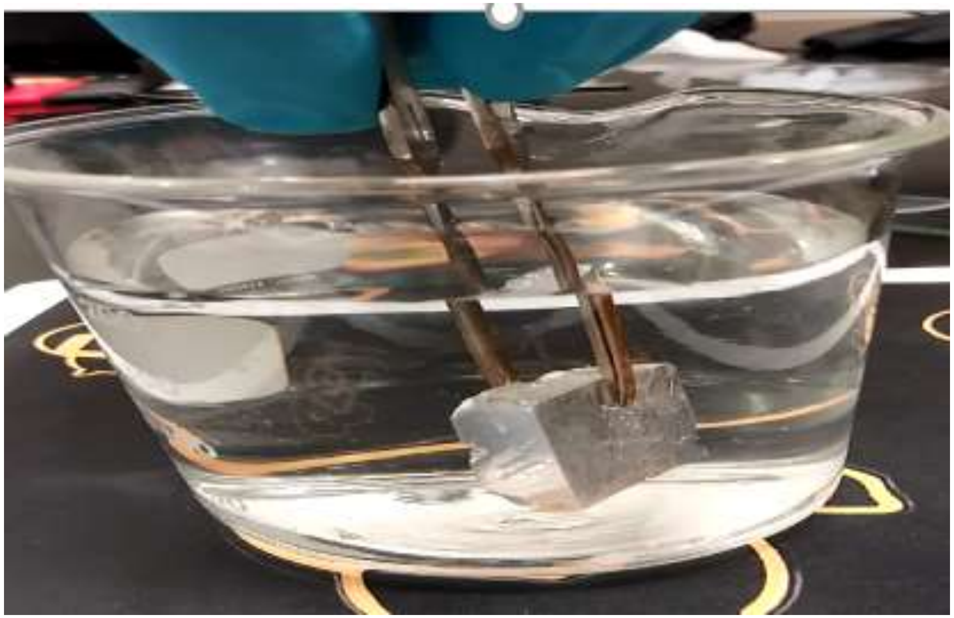
n_a=1.034±0.015

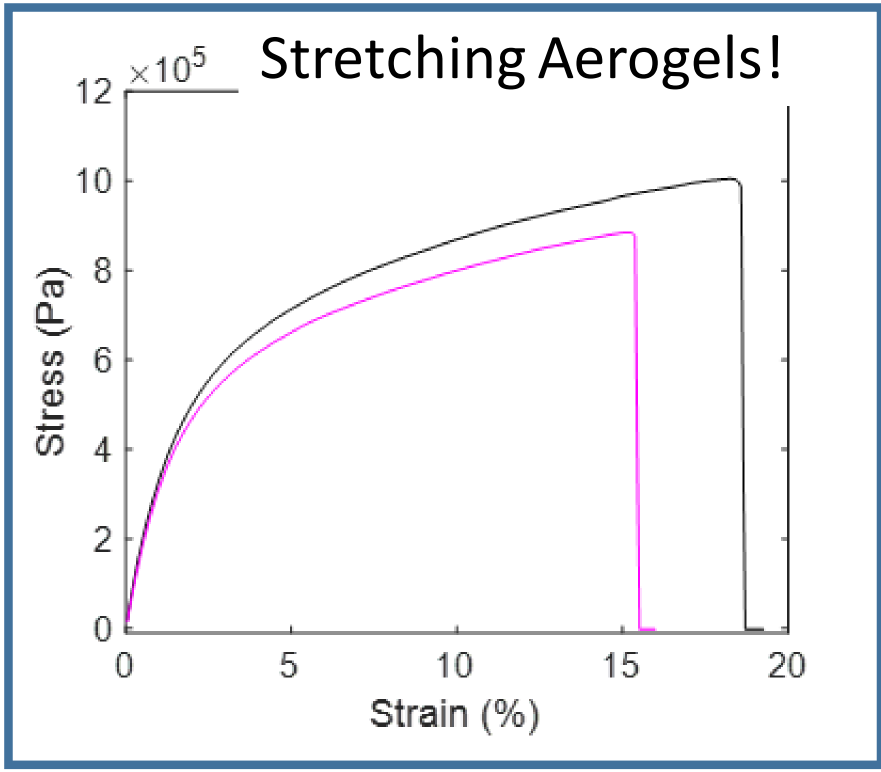


All 3 methods produce consistent data uniform over the large area, repetitive from sample to sample!

Water repellent, super-hydrophobic, flexible/strong

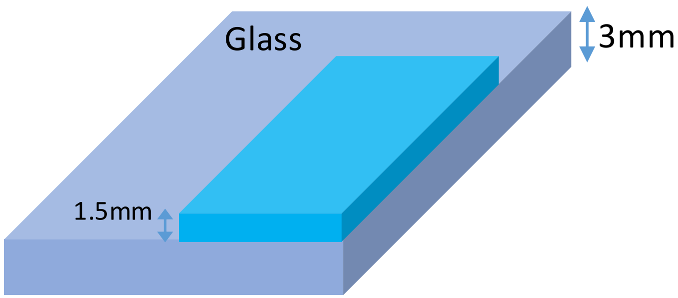
- Our aerogels are highly hydrophobic and water repellent

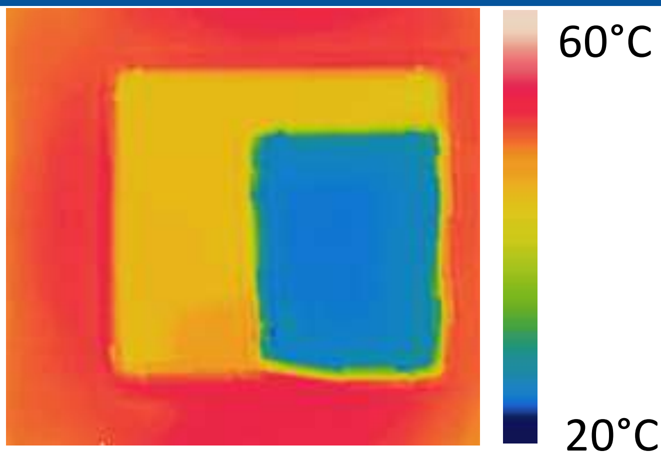


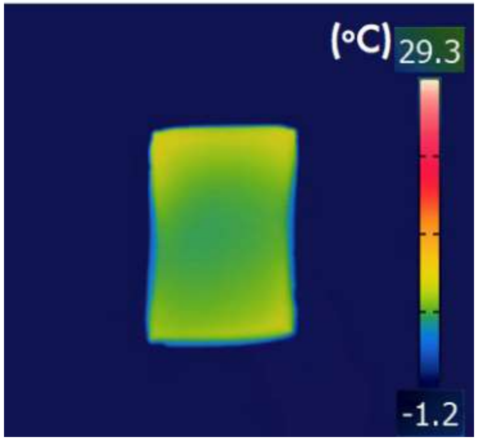


CNF aerogel is tougher & more flexible than other aerogels

Thermal barrier: toward R10 windows

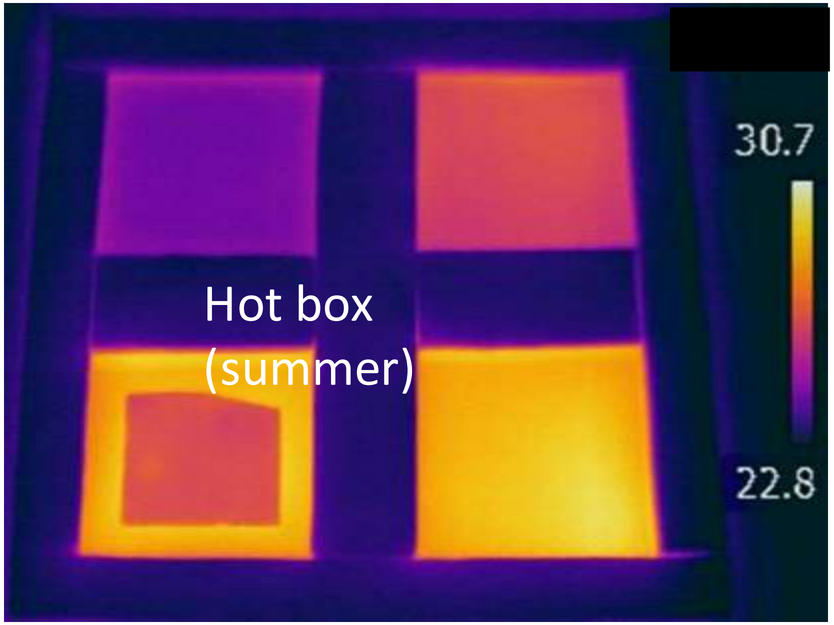


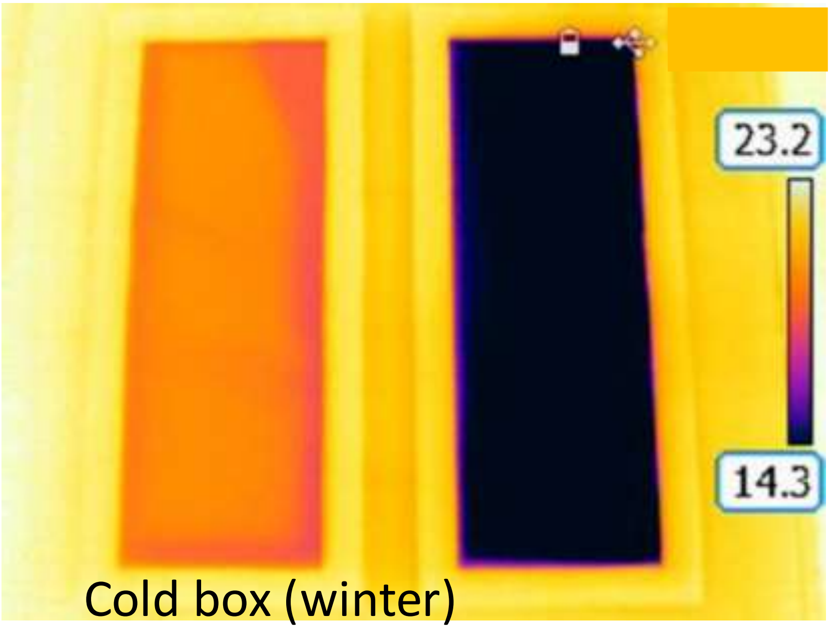




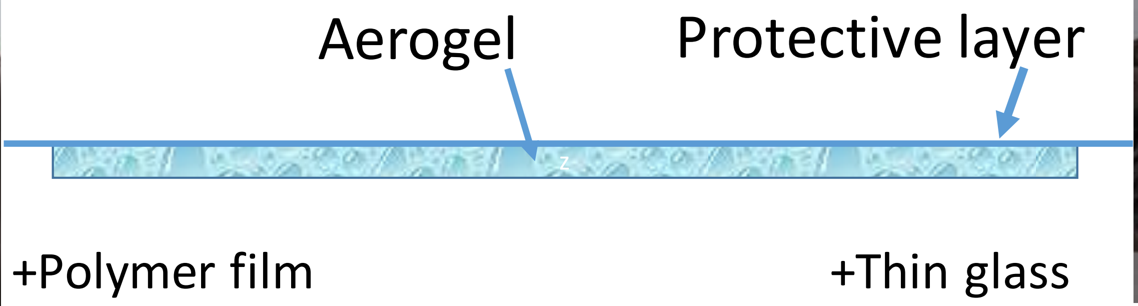
→**11mW/(Km)**

→**Models of homes during winter/summer**

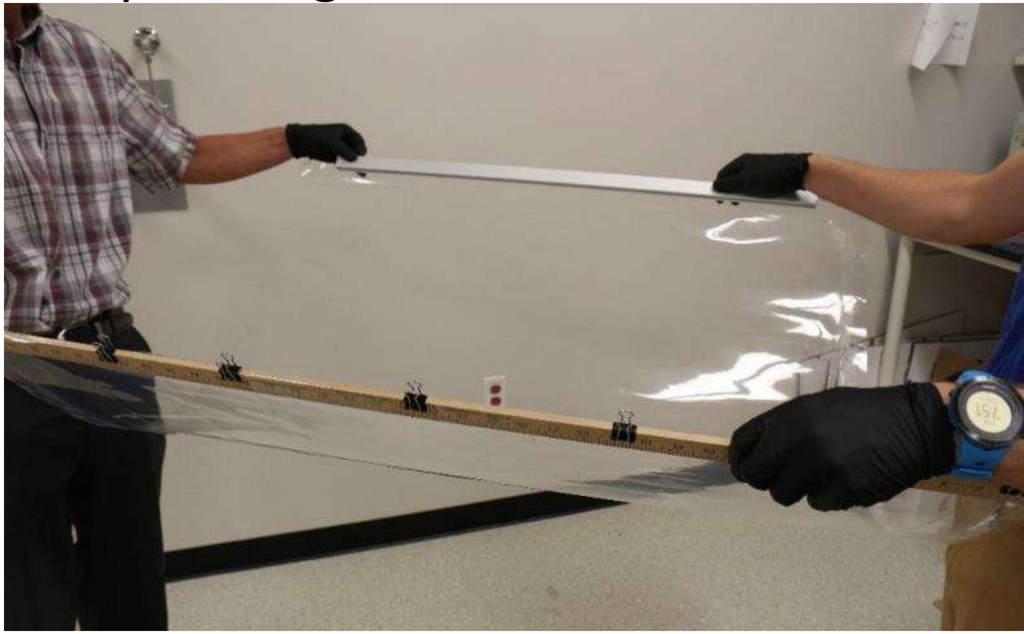




Design & fabrication of the retrofit product

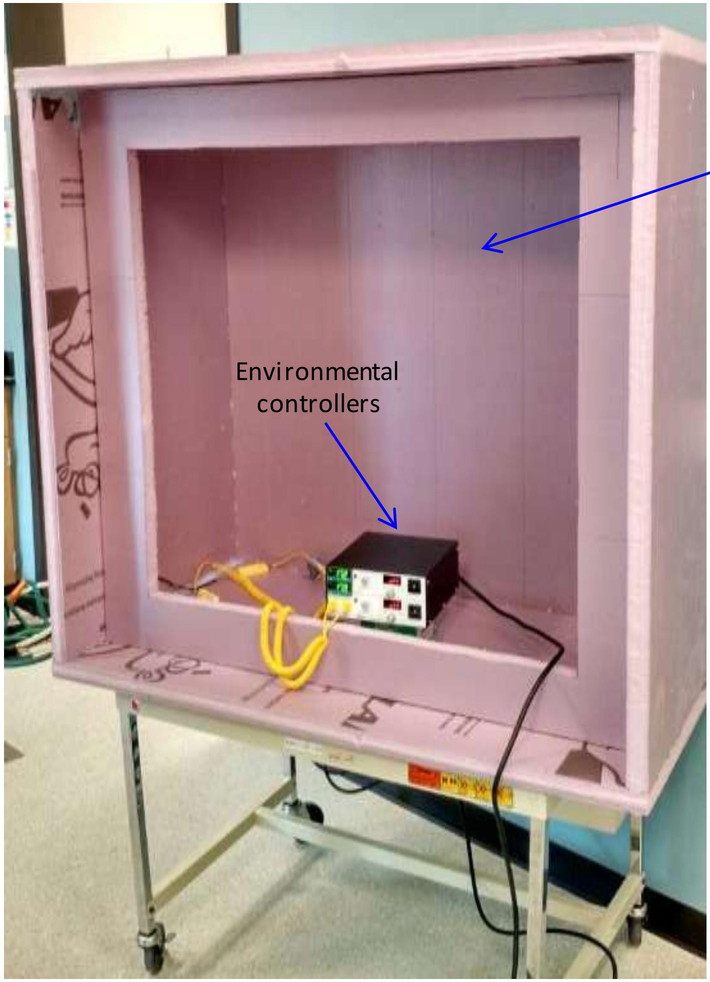


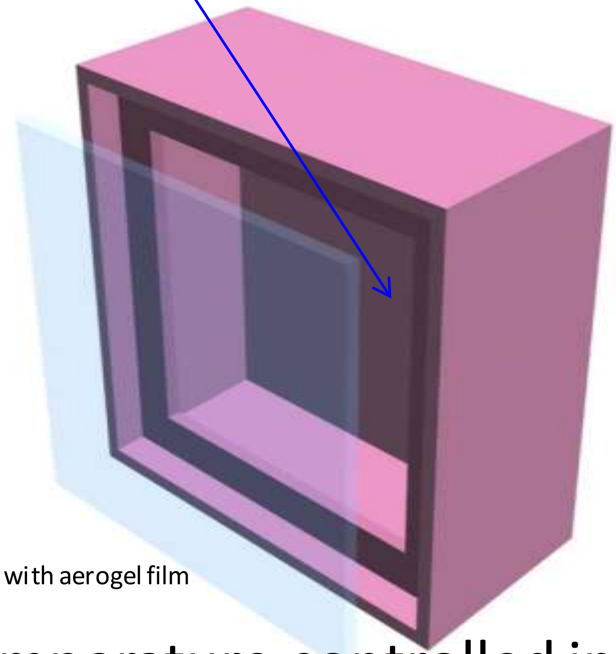
Square meter aerogel on transparent plastic/glass



Environmental hot/cold box chamber

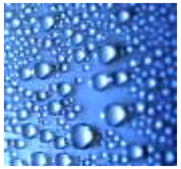
Calibrated hot box chamber for square-meter samples

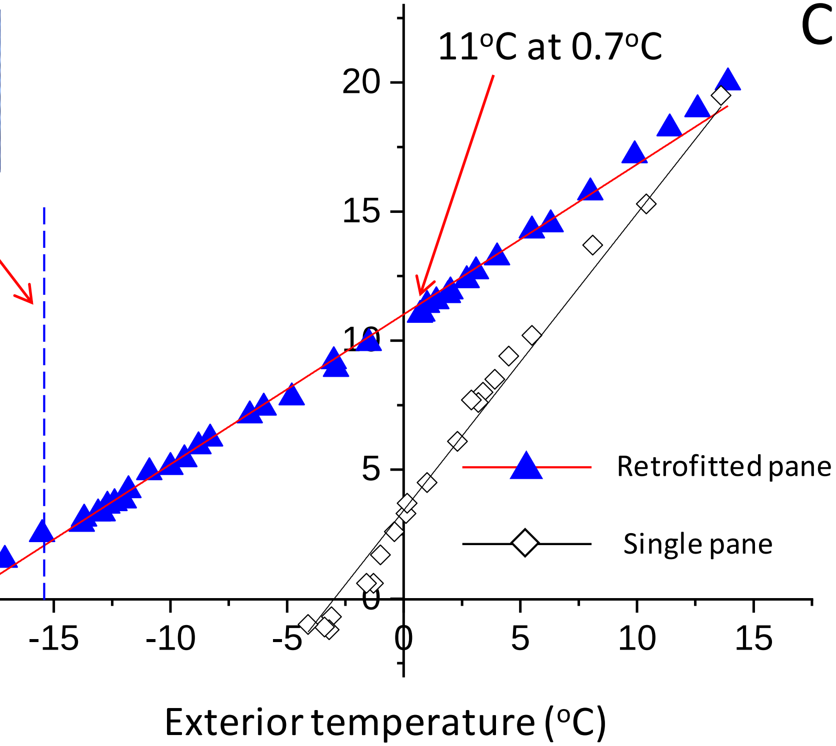




- Temperature controlled in the range –65°C through +100°C
- The indoor humidity controlled in the range 10-90%

Windows comfort parameters





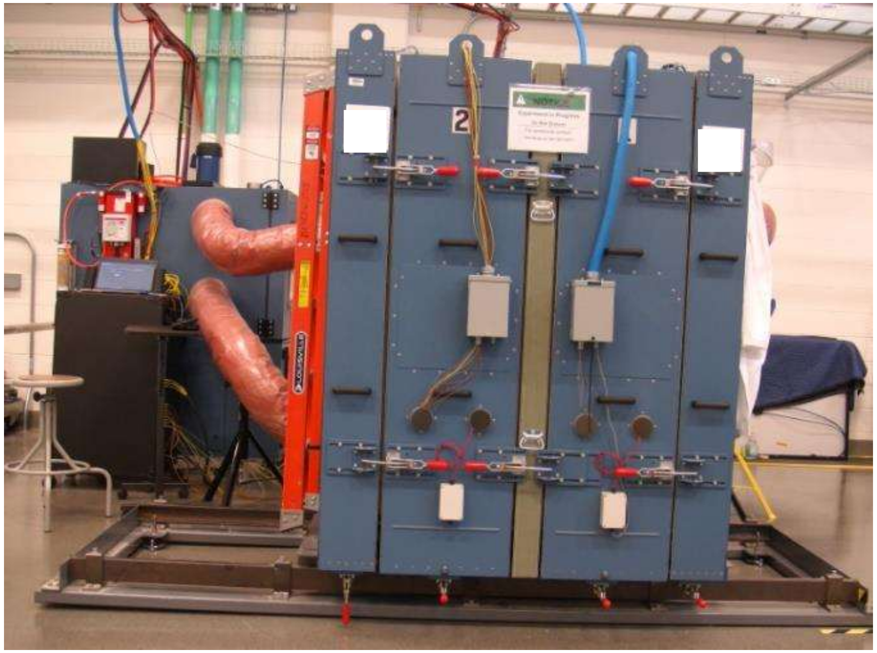
Condensation resistance factor

$$CRF = \frac{T_x - T_e}{T_i - T_e} 100 = 47$$

in the range of CRF=35-50 for double pane windows

- Exterior temperature at which the interior pane surface has temperature of 11°C is 0.7°C, much lower than ~7°C for a single pane window
- Exterior temperature for interior condensation is -15.4°C

Scaling & accelerated lifetime testing

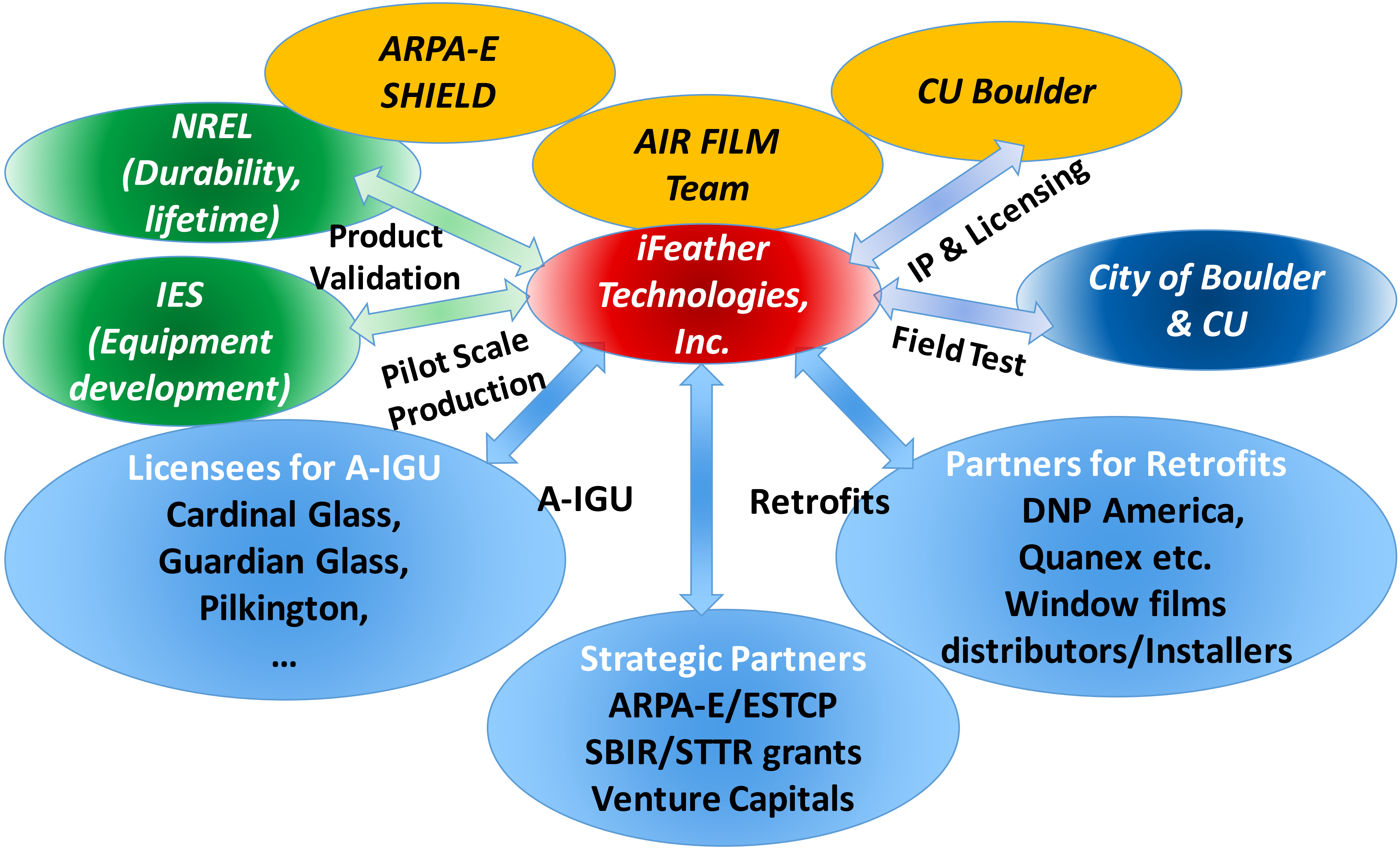


Thermal Cycling, Highly insulating A-IGU windows including framing

7-month durability tests - accelerated modeling & testing lifetime performance

Fabrication: 200 L vessel!!!

Partnerships & strategies



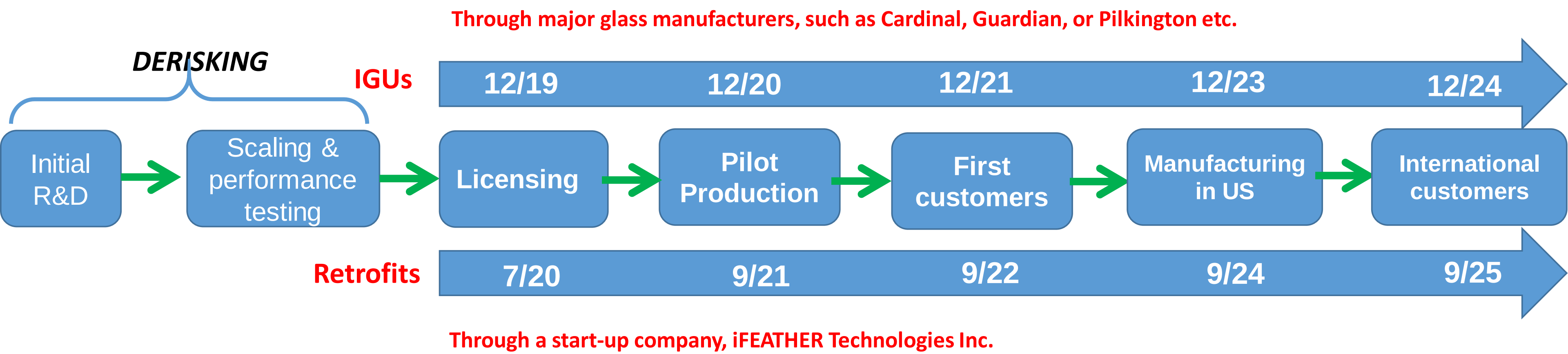
Project outputs

- 6 publications published, 1 in press, 3 to be submitted
- 2 patents, 3 Provisionals, 2 more in preparation
- About 30 NDAs, MTAs & other formal agreements
- ARPA-E summit's central-stage highlight
- 2019 Colorado Lab Venture Challenge winner
- 2018 NASA iTech winner
- Guinness World Record

Project next steps

- For retrofit
  - Licensing & pilot-scale production through **iFeather**
  - **Initial business development** through Colorado Lab Venture Challenge
  - Applying for funding for **Field testing** & **validation**

- For Aerogel-IGU
  - Licensing through major IGU glass manufacturers
  - Further co-development through the iFeather & CU Boulder



Lessons learned

- Materials with >99% transparency are possible
- Aerogels films with haze <1% can be achieved
- Integrating aerogels with protective layers aids in making them even more mechanically robust
- It took ~1year for University of Colorado & Akron University to sign a contract for using facility – involving a startup early on would have saved some time

- "if we could do the project all over again, we'd not assume that we can stay in our laboratory for the entire project duration…"

QUESTIONS?

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Ivan.smalyukh@Colorado.edu

2019 Buildings XIV International Conference

Workshop 8: DOE Building Envelope Research Projects on Fenestration and Grid Interaction

Shannon Poges, PhD
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Deposited Aerogel Coatings as Thermal Insulation for Windows

Acknowledgements

ARIZONA STATE UNIVERSITY

nanoparticle depositions, optical characterization, prototype fabrication

Prof. Zachary Holman Principal Investigator	**Shannon Poges** Postdoc Coating Deposition / Characterization	**Joe Carpenter** PhD Student SEM/TEM	**Laurel Passantino** General Staff Project Organization
	Mark Li PhD Student Coating Depositiont	**Zach Leuty** PhD Student Coating Deposition	**Rob Stirling** General Staff Techno Economic Analysis

COLORADO SCHOOL OF MINES

thermal characterization

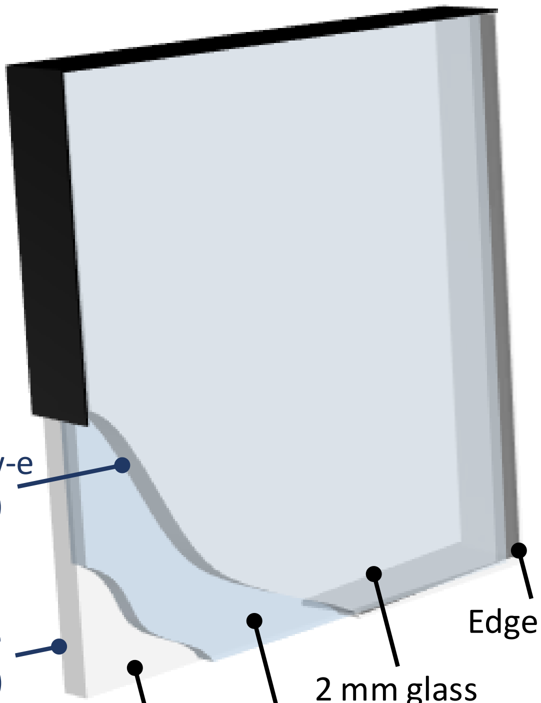
Prof. Eric Toberer Thermal and Mechanical Properties	**Jesse Adamczyk** PhD Student Thermal Modelling

UNIVERSITY OF MINNESOTA

nanoparticle / flow simulations
thermal modeling

Prof. Chris Hogan Flame Synthesis	**Jihyeon Lee** PhD Student Porous Film / Heat Transfer Modeling	**Yeonshil Park** Postdoc Particle / Nozzle Simulation

Product Overview



The Problem:

- Thin glass with superior thermal performance.
  - Not Available

Our Solution:

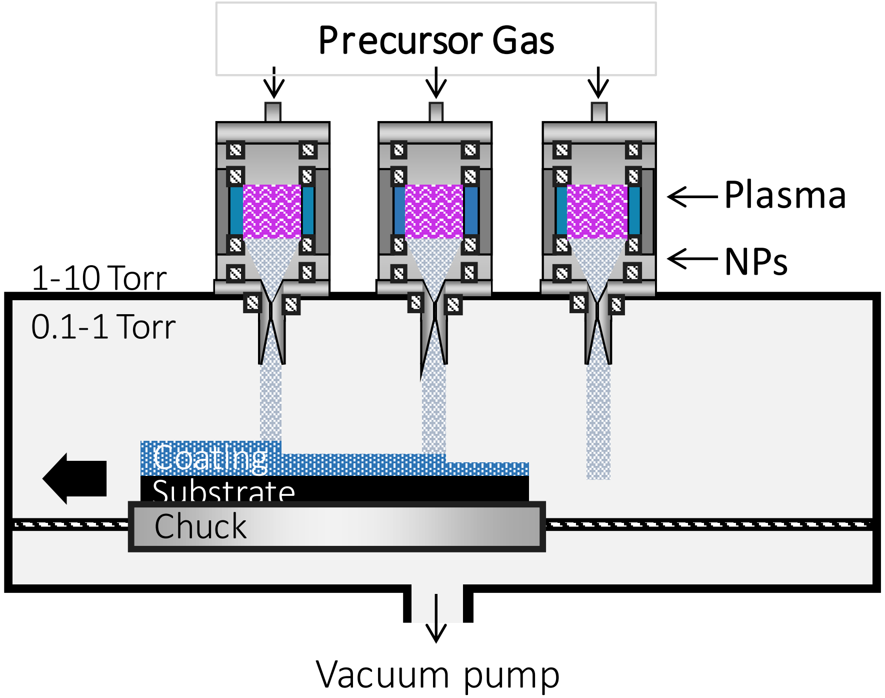
- Water-impermeable, durable,<7-mm-thick Glass/Coating/Glass package.
  - ***single-pane form factor, double-pane performance***

- Technical approach
  - Aerosol Impaction Driven Assembly (AIDA)

Product Innovation

- ***Plasma synthesis of SiO_2 nanoparticles***
  - 5 nm in diameter, controlled via residence time in plasma
  - SiH_4 and air are precursors to synthesis

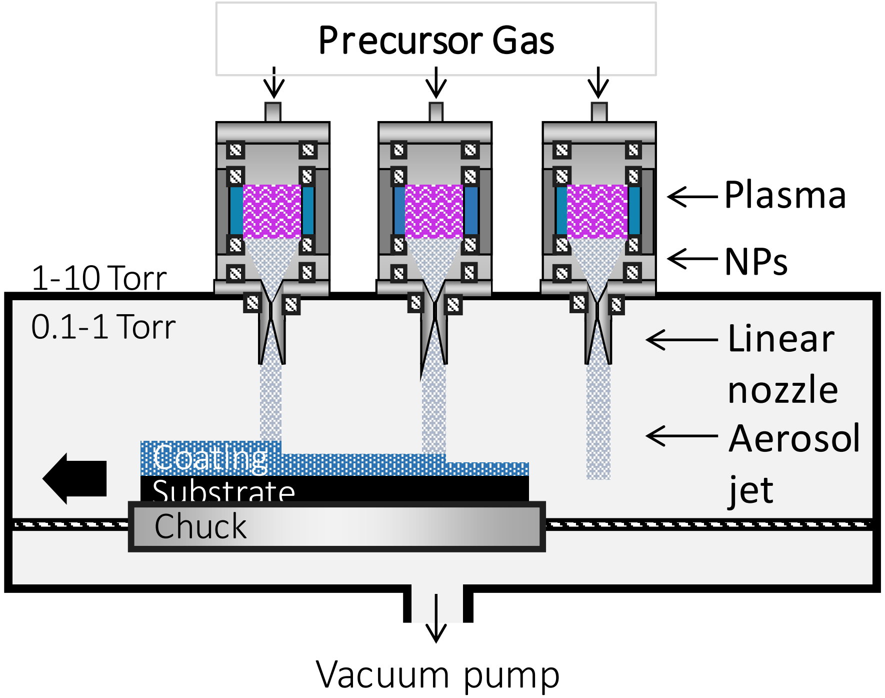
Aerosol Impaction Driven Assembly (AIDA)



Product Innovation

- ***Plasma synthesis of SiO_2 nanoparticles***
  - 5 nm in diameter, controlled via residence time in plasma
  - SiH_4 and air are precursors to synthesis
- ***Spray deposition of aerosol onto glass***
  - Acceleration through nozzle into continuously evacuated chamber
  - Controllable particle impact velocity translates to controllable film porosity (5-95%) and thermal conductivity.
  - Linear, scalable source (slit nozzle) in series to meet desired line speed

Aerosol Impaction Driven Assembly (AIDA)



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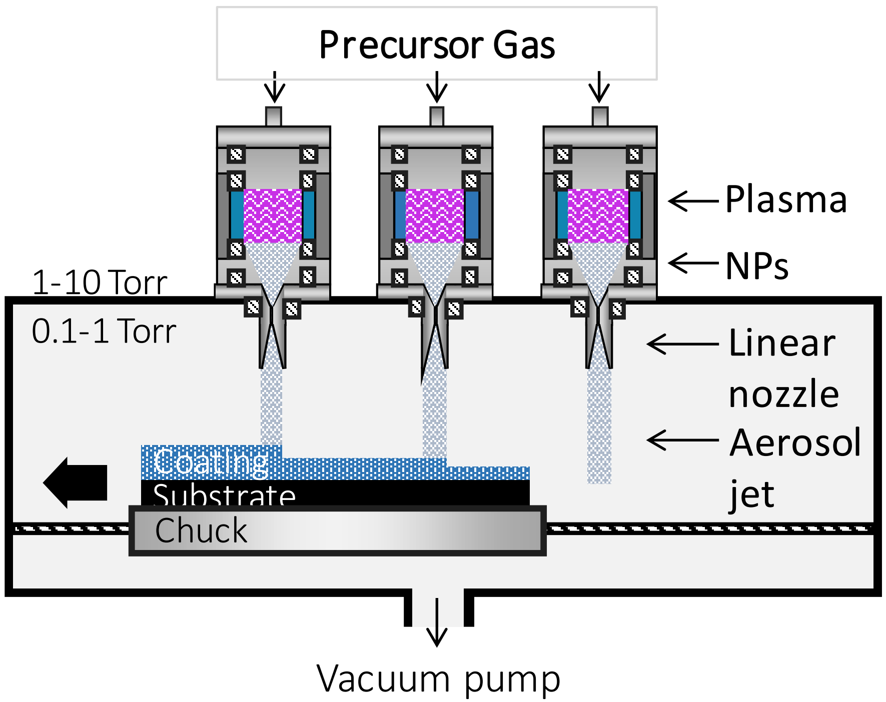
  - Linear, scalable source (slit nozzle) in series to meet desired line speed
- ***Environmental isolation with outer glass***

Aerosol Impaction Driven Assembly (AIDA)



Target Technical Metrics

- ***Single-pane replacement***

U-factor (BTU/sf/F/hr)	T_{vis} (%)	Haze (%)	Lifetime (Years)	COGS ($/ft²)
0.4	>60	<1	>20	<10

- IP and know-how in window product, coating hardware/ process, and raw materials

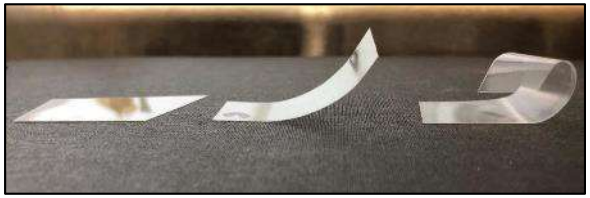
- Start-up company commercializing coating deposition method for other applications; business model is to provide licensed deposition hardware and coating materials.

200 µm

1 mm

Deposition / Structure Evolution

Deposition on plastic film



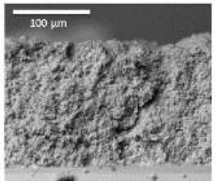
PET Substrate

1 µm Coating

5 µm Coating

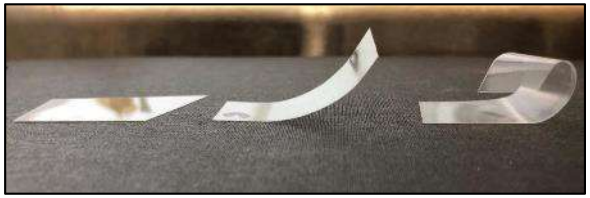
Q1

Flame Synthesis



Deposition / Structure Evolution

Deposition on plastic film

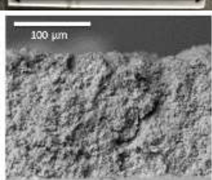


PET Substrate | 1 µm Coating | 5 µm Coating

Deposition on glass

Q1 — **Q4**

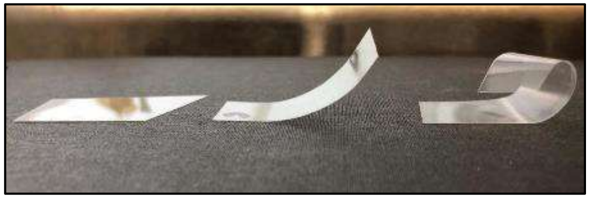
Flame Synthesis



Plasma Synthesis
100 nm → 100 µm

Deposition / Structure Evolution

Deposition on plastic film



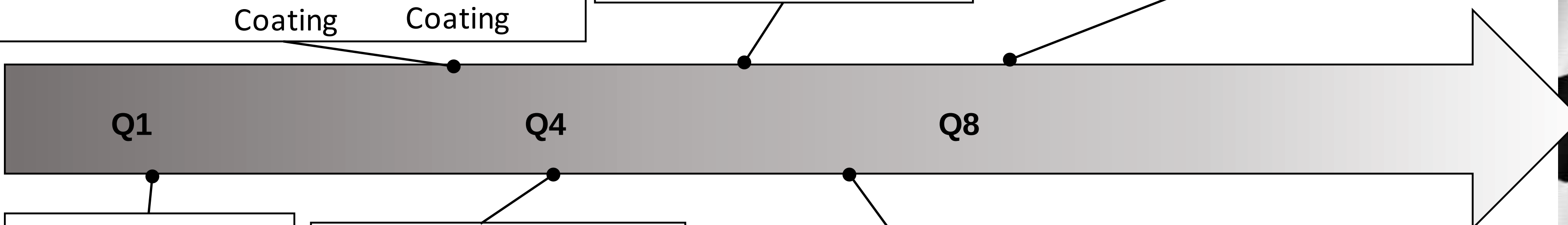
PET Substrate

1 µm Coating

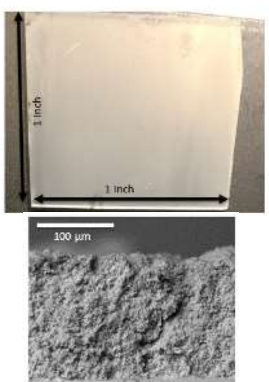
5 µm Coating

Deposition on glass

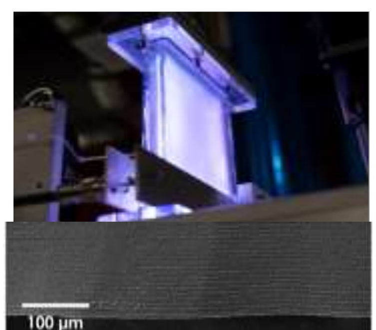
Glass-glass package with edge seal



Flame Synthesis



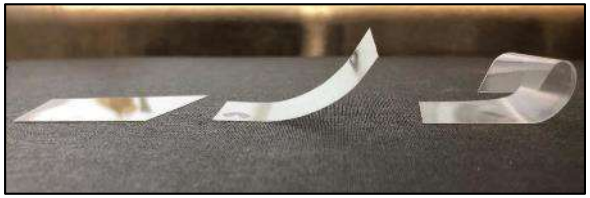
Plasma Synthesis
100 nm → 100 µm



First Prototype
(1 mm) Haze 23%

Deposition / Structure Evolution

Deposition on plastic film



PET Substrate

1 µm Coating

5 µm Coating

Deposition on glass

Glass-glass package with edge seal

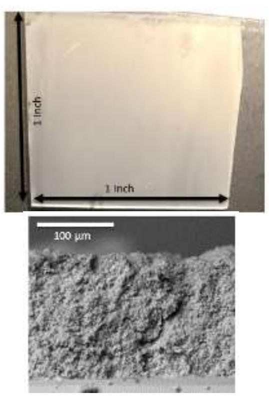
Q1

Q4

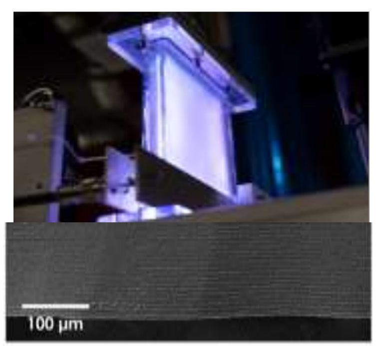
Q8

Q12

Flame Synthesis



Plasma Synthesis 100 nm → 100 µm

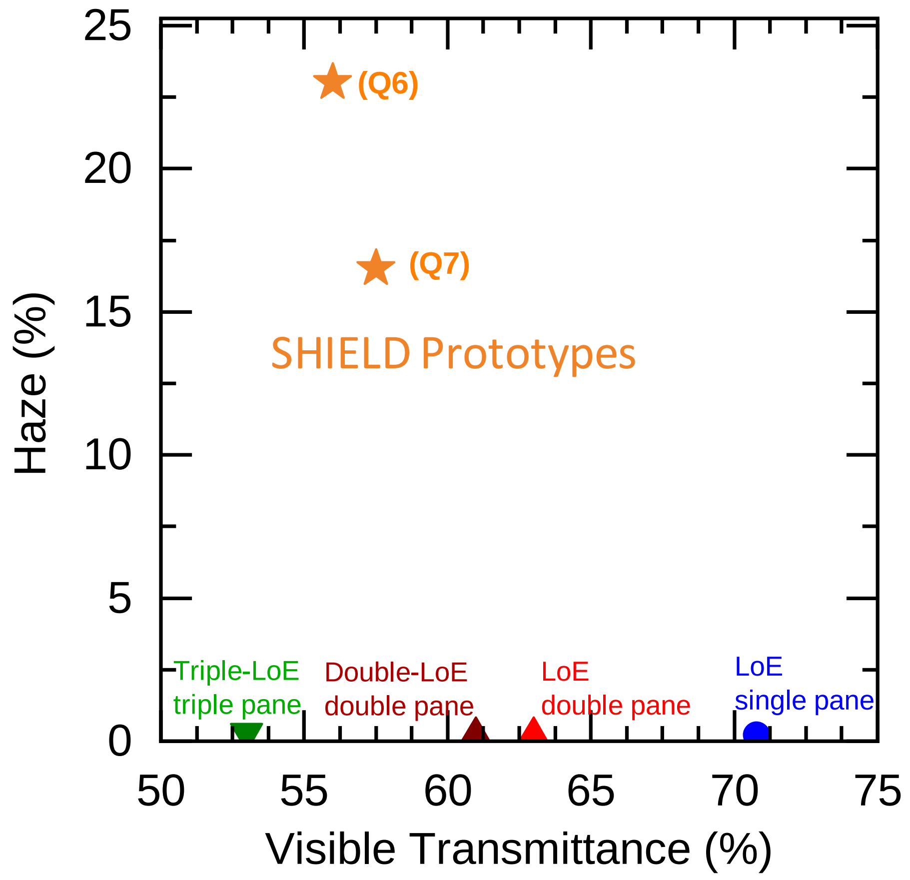


First Prototype (1 mm) Haze 23%

Current Prototype (1 mm) Haze 6.5%

Optical Properties

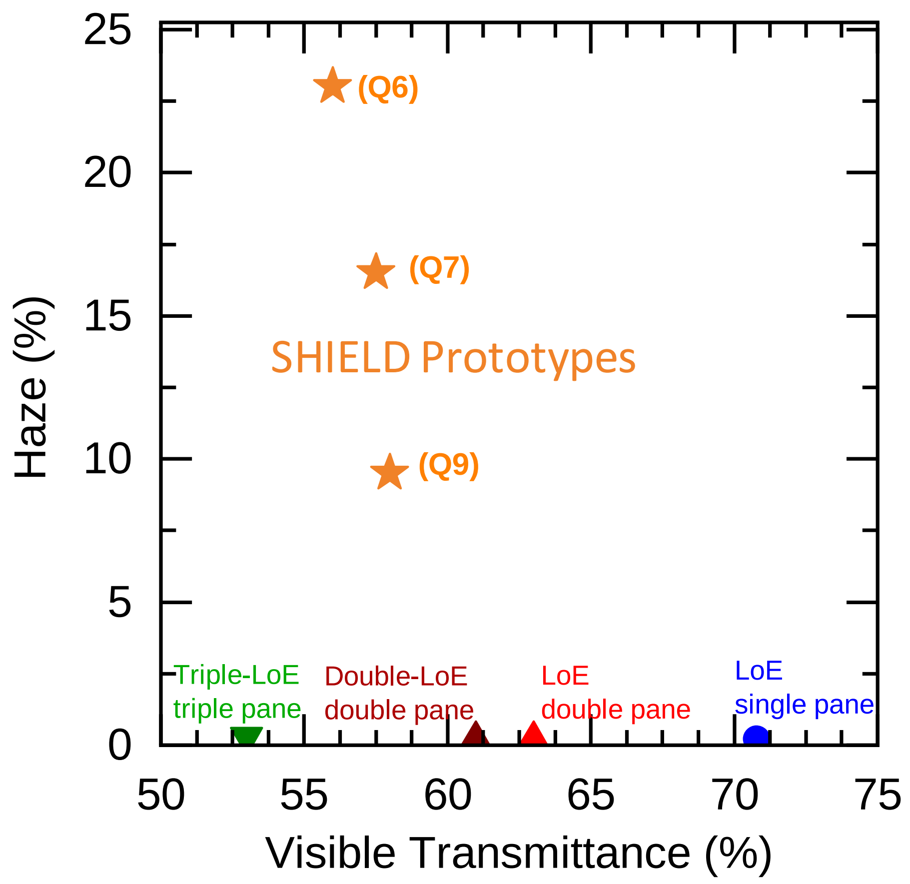
- Started using plasma in **Q4**.
  - First 1 mm demonstration Q6.
- **Q6 – Q7**
  - Optimized process conditions



Optical Properties

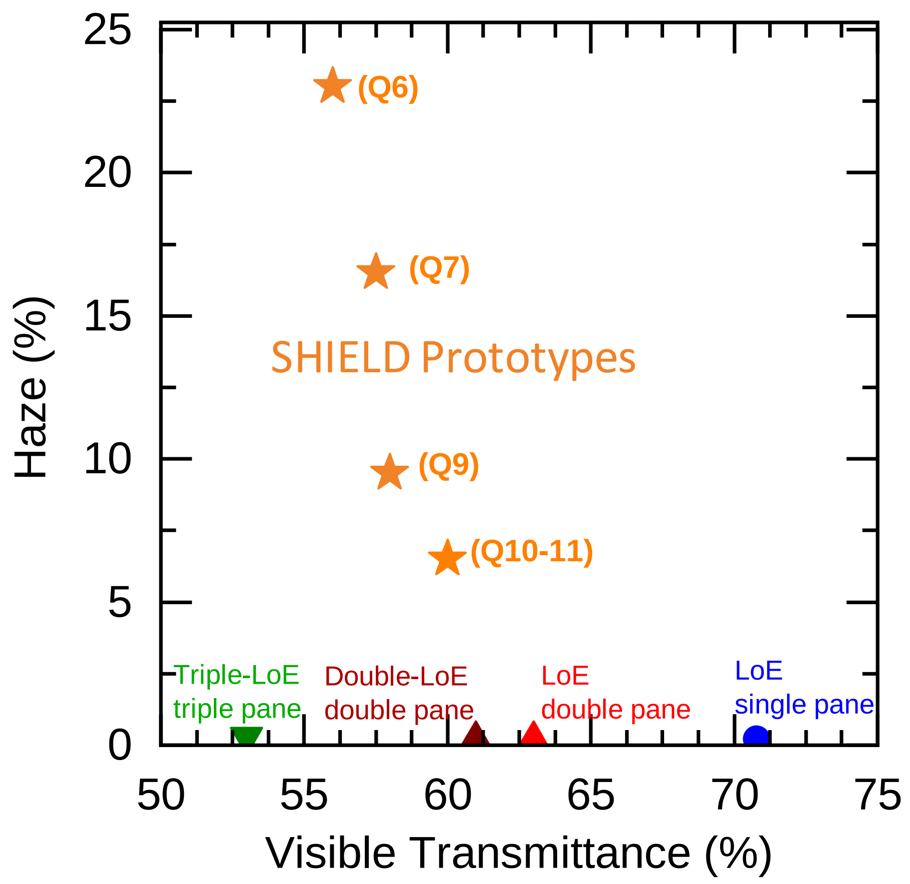
- Started using plasma in Q4.
  - First 1 mm demonstration Q6.

- **Q6 – Q7**
  - Optimized process conditions
- **Q7/8 – Q9**
  - + Impactor



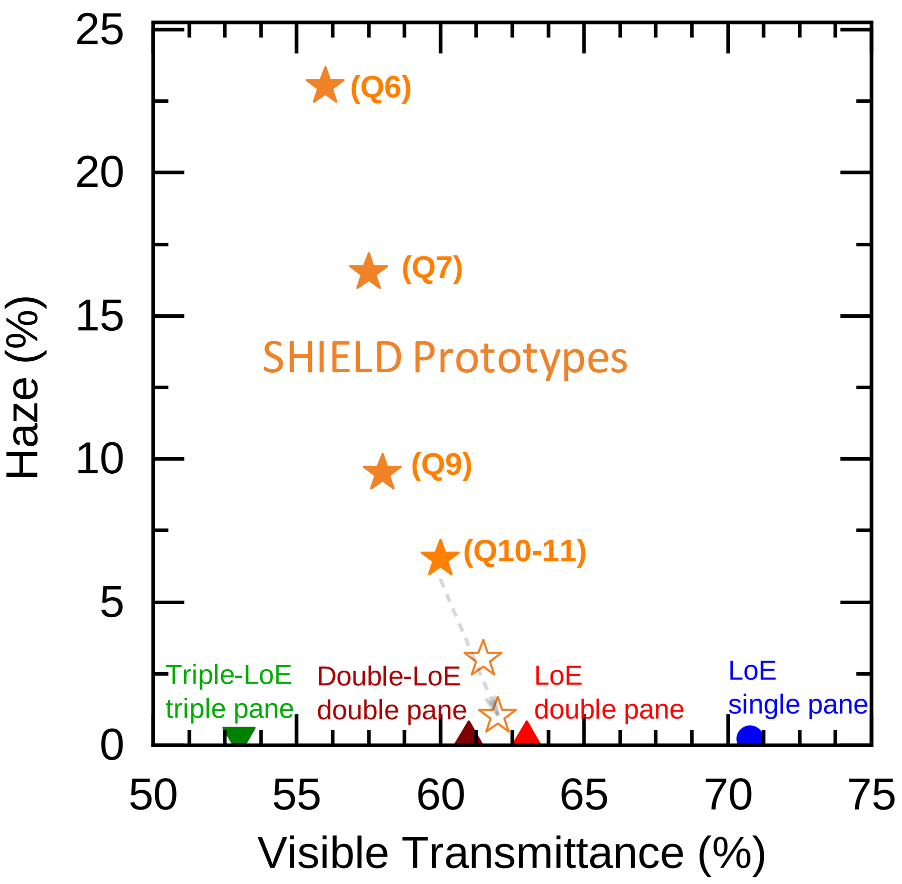
Optical Properties

- Started using plasma in Q4.
  - First 1 mm demonstration Q6.
- **Q6 – Q7**
  - Optimized process conditions
- **Q7/8 – Q9**
  - + Impactor
- **Q9 – Q10/11**
  - Optimized throughput
  - Reactor re-design



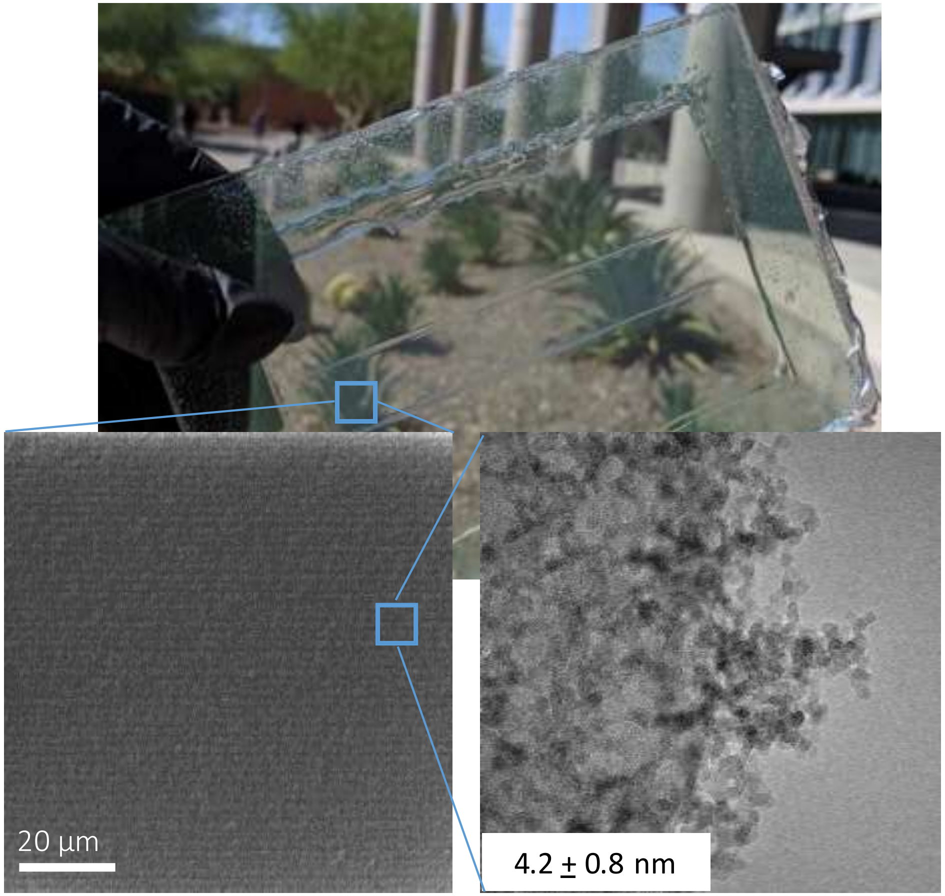
Optical Properties

- Started using plasma in Q4.
  - First 1 mm demonstration Q6.
- **Q6 – Q7**
  - Optimized process conditions
- **Q7/8 – Q9**
  - + Impactor
- **Q9 – Q10/11**
  - Optimized throughput
  - Reactor re-design
- **Q11 – Q12**
  - Reduced particle agglomeration
  - Reduced surface roughness



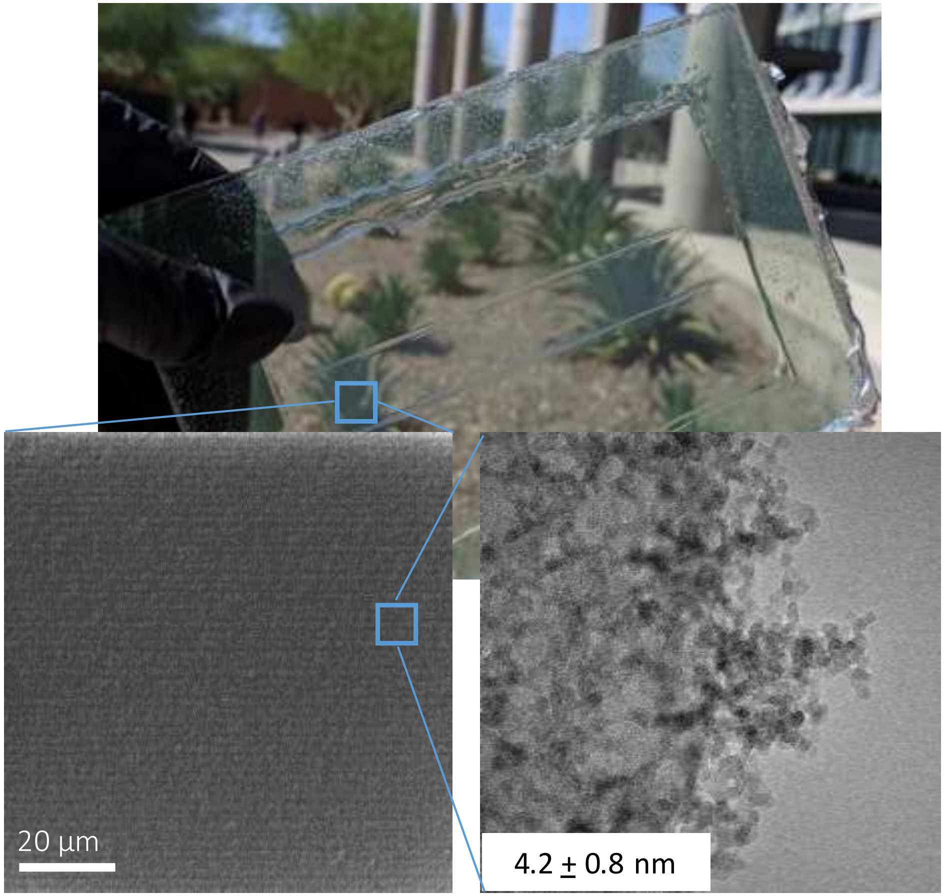
Optical Properties

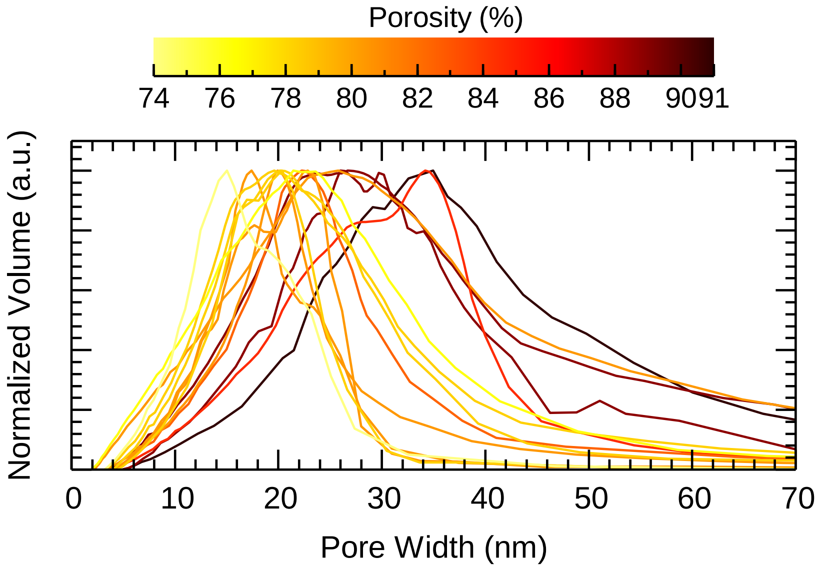
- Current Haze (6.5%)

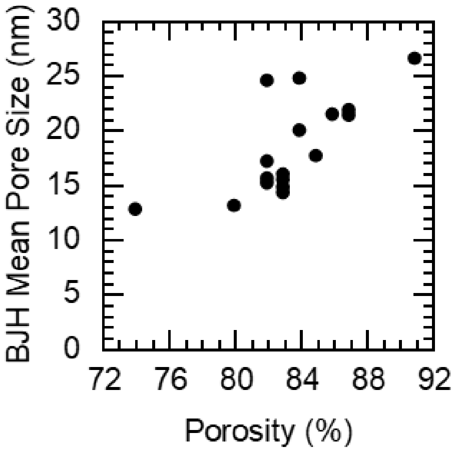


Optical Properties

- Current Haze (6.5%) and Pore Diameter (15 nm)



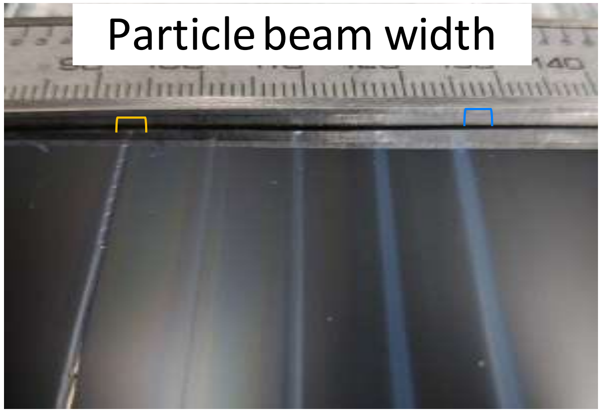


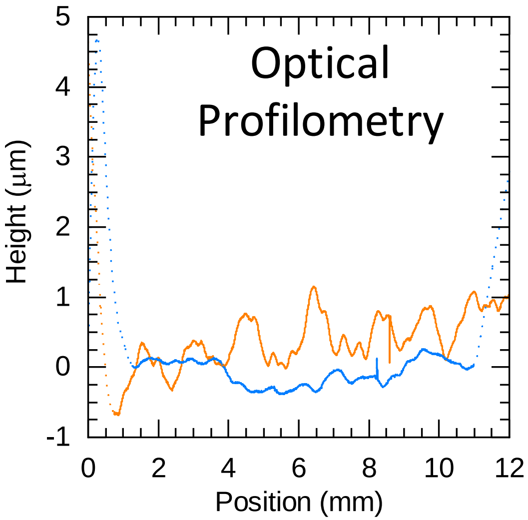


Optical Properties – Reducing Haze

- Surface Scattering
  - Translation "chatter"
    - tool re-design
    - nozzle re-design

Particle beam width





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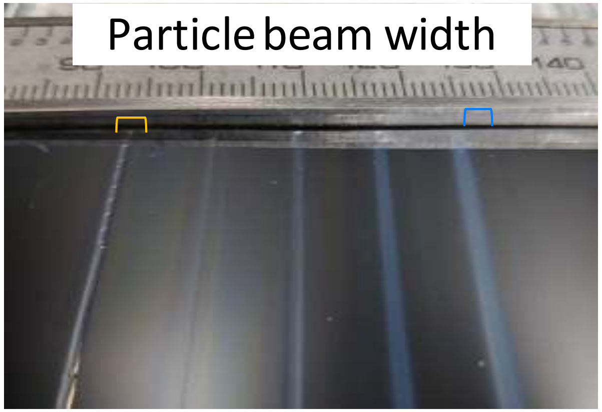
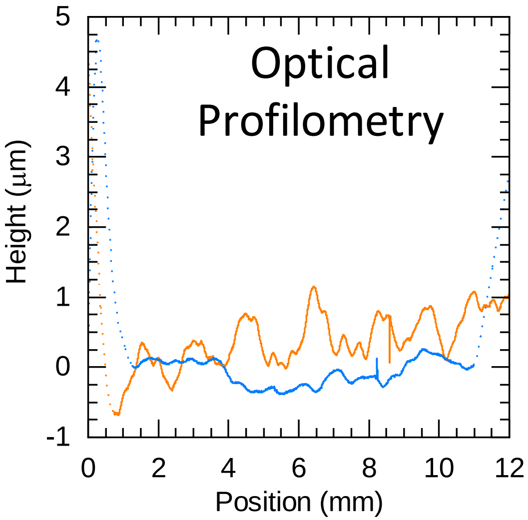
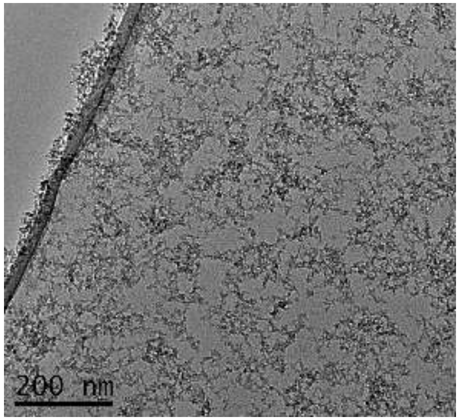


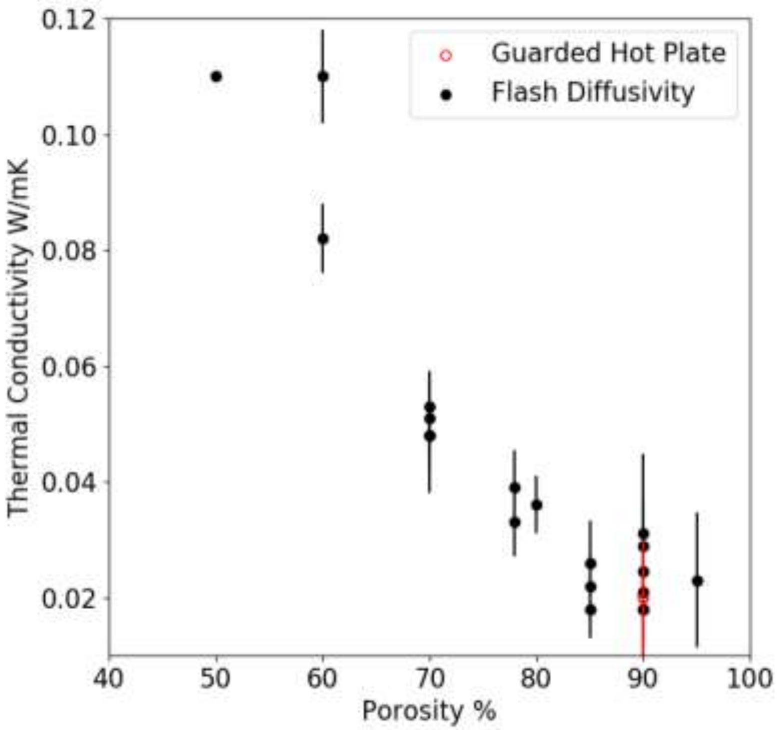


- Bulk Scattering
  - Reduce large pores> 30 nm
    - decrease agglomeration



Thermal Properties

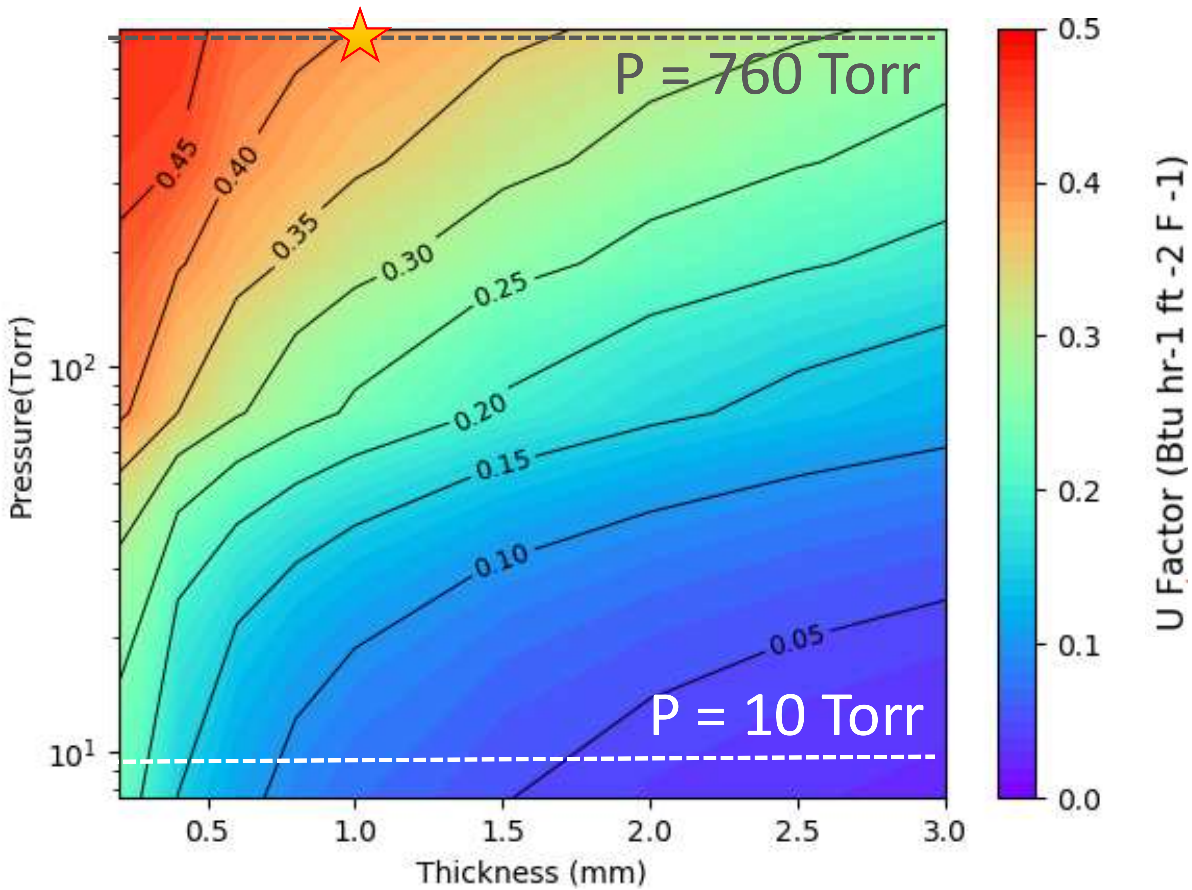
- Thermal Conductivity
  - Guarded hot plate @ CSM



Measured Thermal Conductivity for 200 µm SHIELD Prototype	Calculated (THERM) U-Factor for 1 mm SHIELD Prototype
0.02 ± 0.005 W/mK	0.437 BTU/sf/hr/F

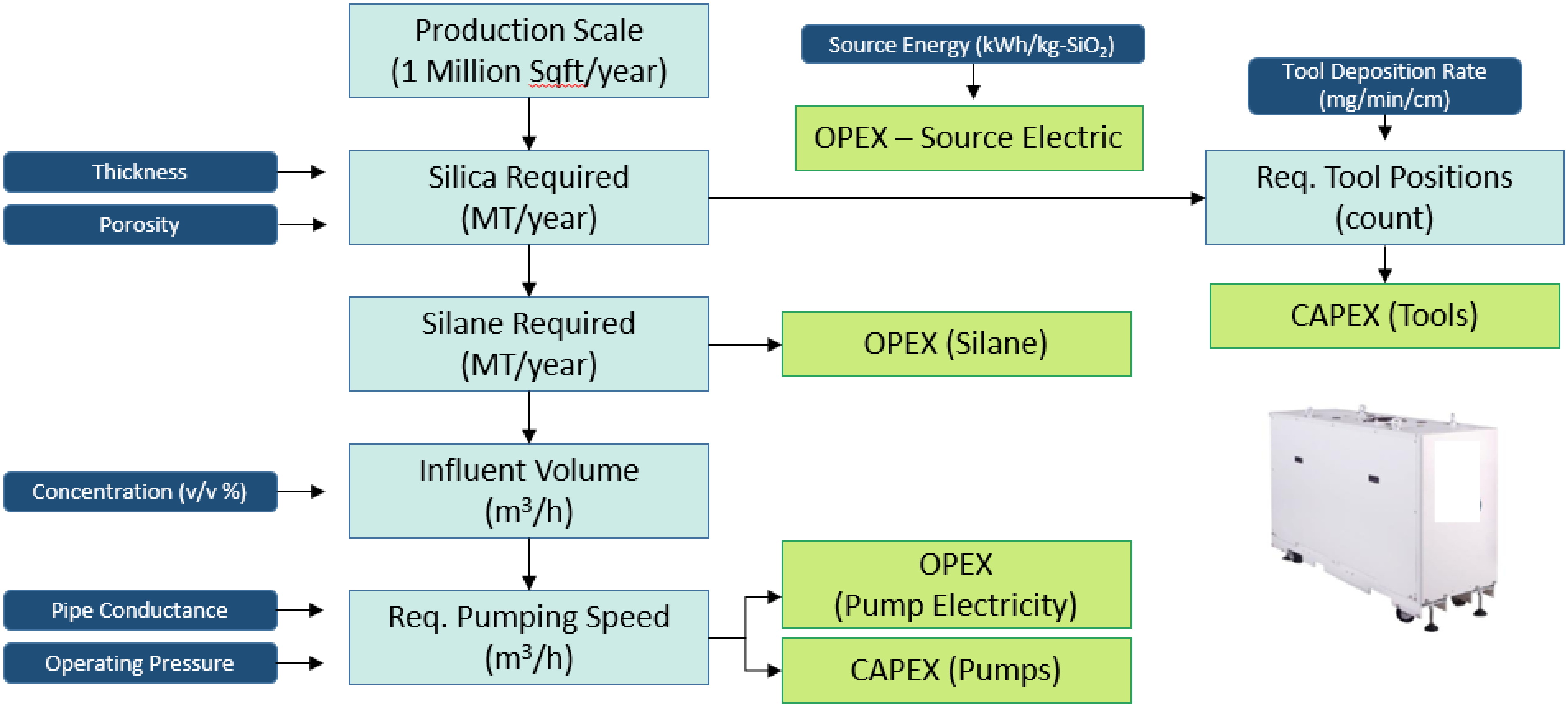
Thermal Properties

- U- Factor
  - Calculated with THERM



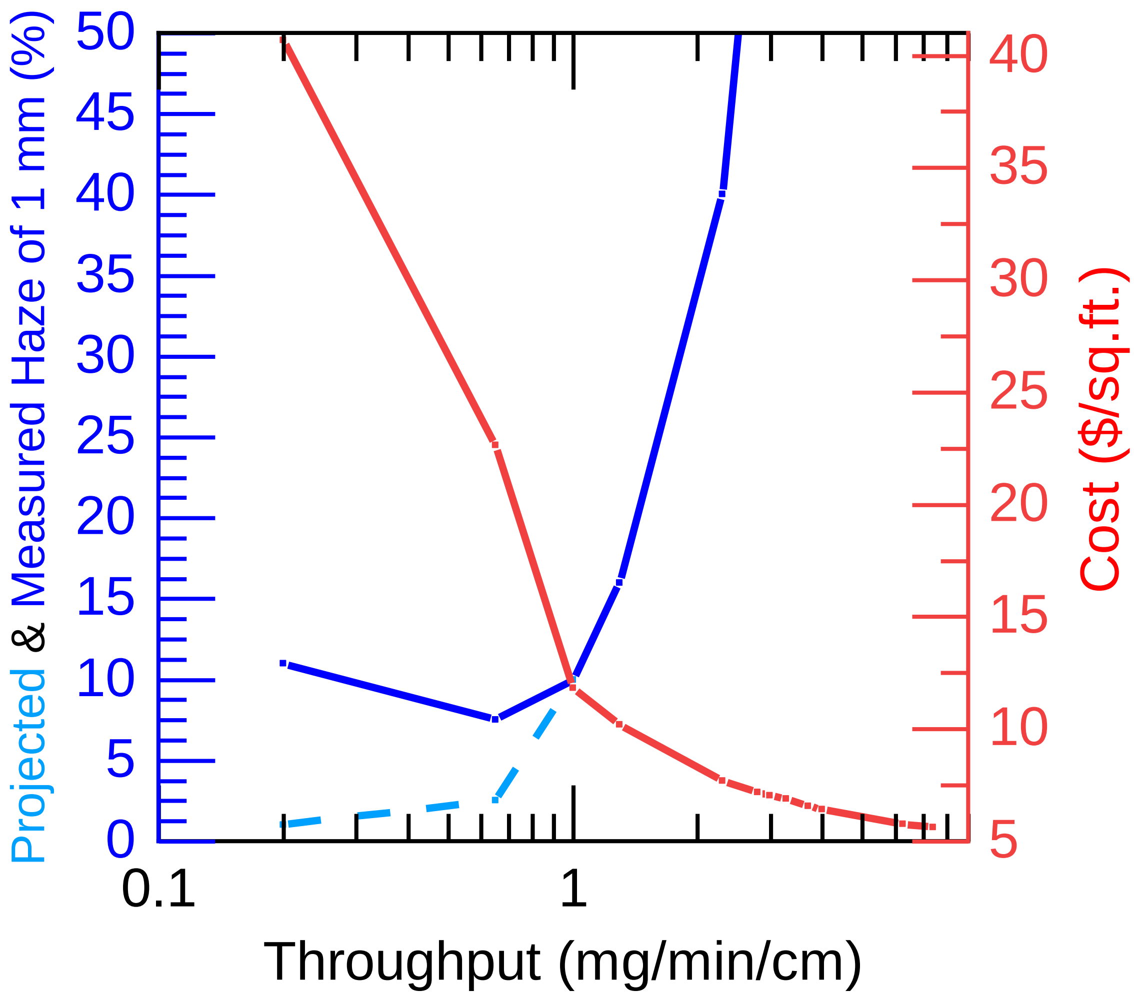
Visualization of Techno-Economic Model

Plasma / Silane Route



Visualization of Techno-Economic Model

Dependence on Haze/Throughput



*Data based on 5% Silane, 1 mm coating

Timeline

Prototype → **Commercialization**

1-mm-thick 3.5” x 5” demonstrated with <5% Haze

Implement new hardware to lower bulk scattering

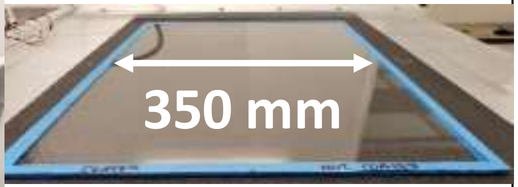
Implement new hardware to lower surface scattering

Pass all window standards with SHIELD window product

ASTM ###

ISO ###

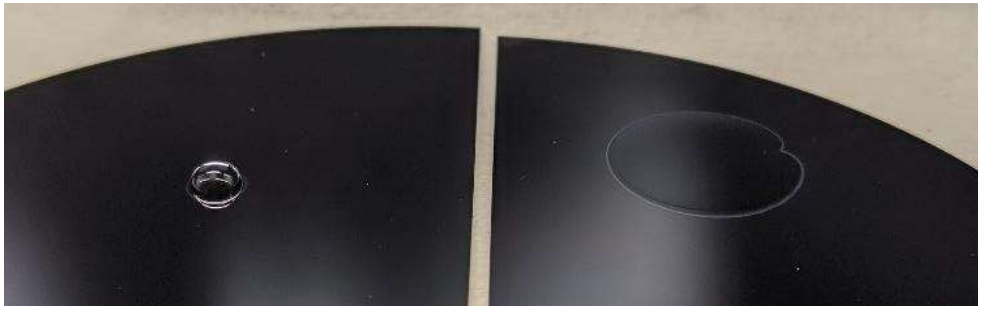
Scaling to 14” x 24”; 8 hours run time



Demonstrate full SHIELD window product on 14” x 24” scale

Other Project Output

- **Hydrophobic coatings**
  - Increased ambient working time 10x.



SHIELD Coating + hydrophobic coating

SHIELD Coating

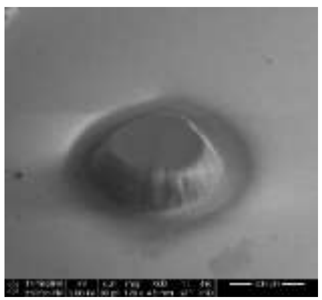
- **Thermal insulation for Semiconductor devices**
  - Isolation of selected areas

Dry Etching

Silica coating after spinning and patterning positive resist, dry etching, and resist stripping, showing successful patterning of a 50% porous layer

Other Project Output

- **VIG Pillars**
  - Continued interest in transparent, thermally insulating VIG pillars from IGU manufacturers



  - Failure strength is low; thermal conductivity and transparency are exceptional

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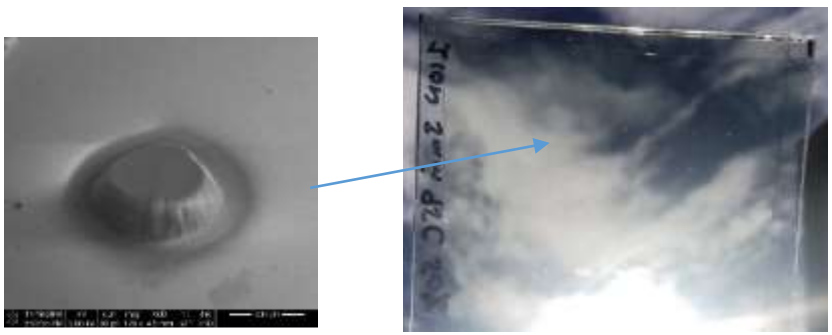
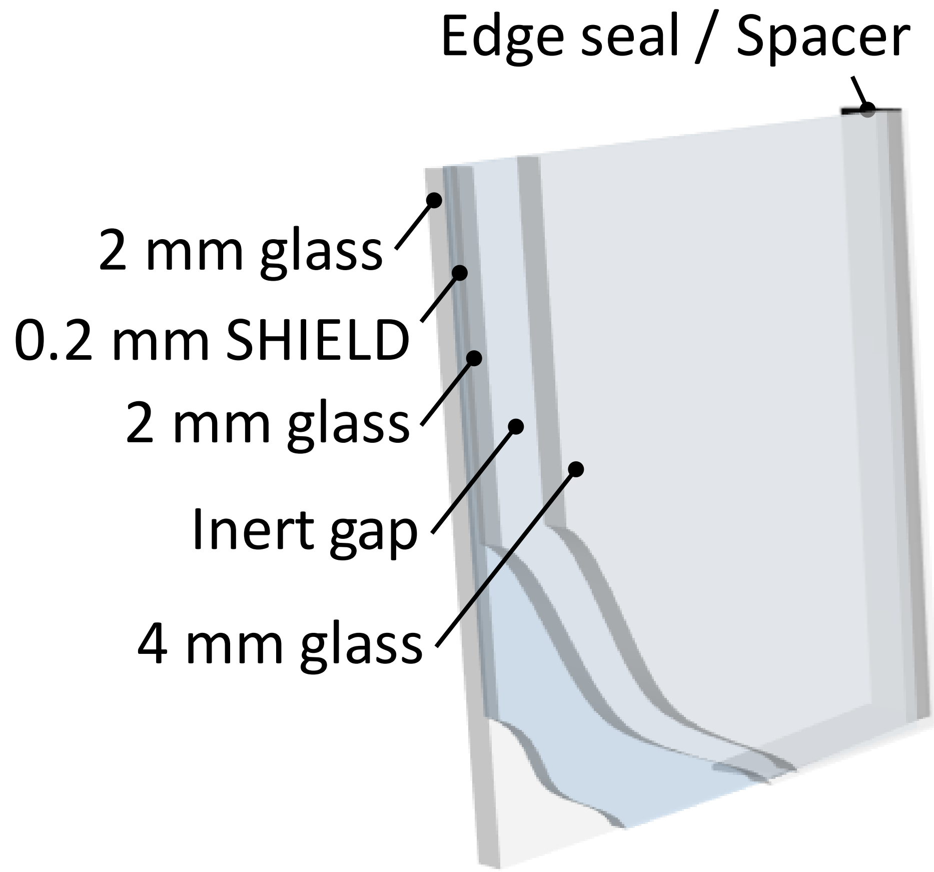


  - Failure strength is low; thermal conductivity and transparency are exceptional

- **Thinner coatings within multi-pane IGUs**



Bibliography

- U.S. Patent No. 10,092,926 B2. Oct, 2018.
- Holman, Z.C., Firth, P. *Aerosol Impaction-Driven Assembly System for the Production of Uniform Nanoparticle Thin Films with Independently Tunable Thickness and Porosity*. ACS Appl. Nano Mater. 2018, 1, 4351-4357.
- Dr. Cenk Kocer at U. Sydney, VIG expert analysis

Questions?

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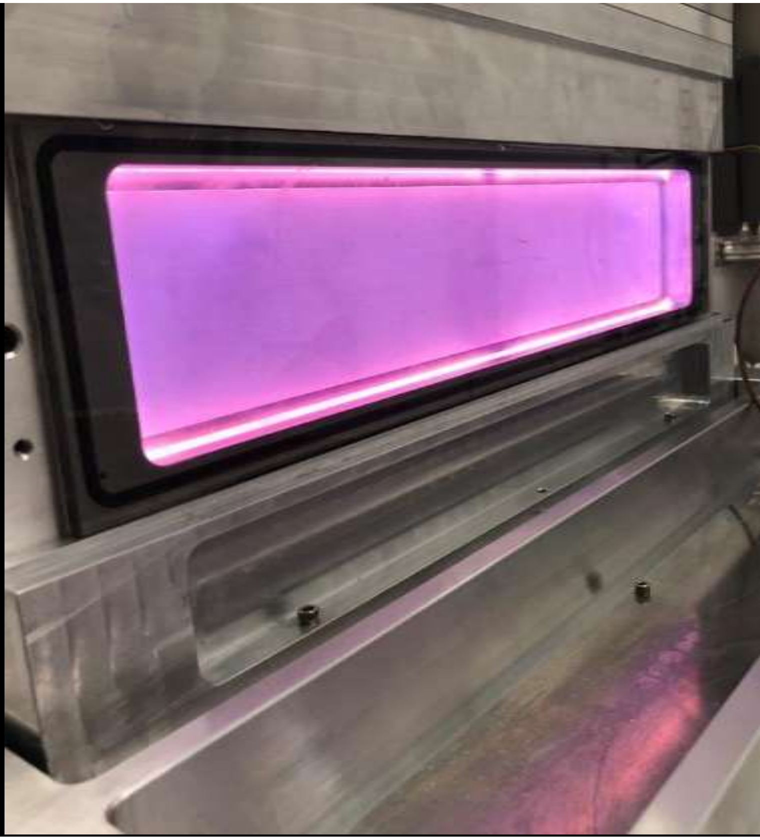

Workshop 8: DOE Building Envelope Research Projects on Fenestration and Grid Interaction

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parc
A Xerox Company

All-polymer transparent thermal barriers

Acknowledgements

- ARPA-E team for funding and guidance

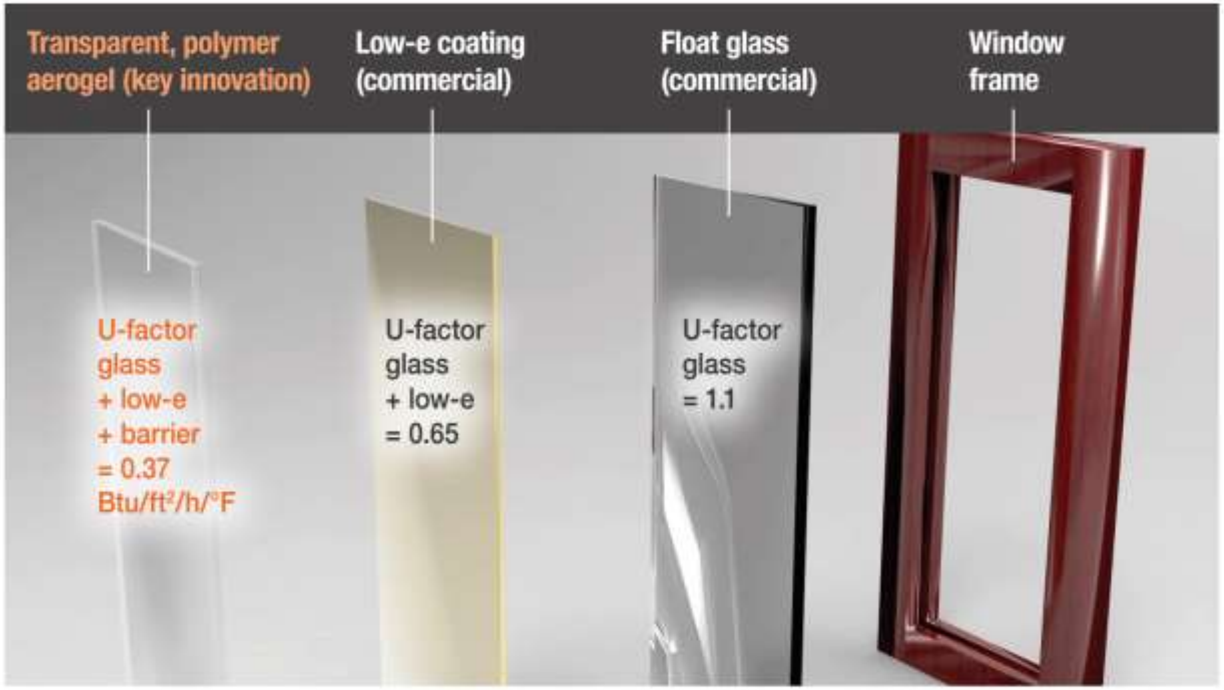
Helpful discussions with:

- Keith Burrows, Cardinal Glass
- Ashtosh Ganjoo, Vitro
- Stephen Selkowitz, Lawrence Berkeley Lab
- Zachary Holman, Arizona State University
- Wendell Rhine and Shannon White, Aspen Aerogels

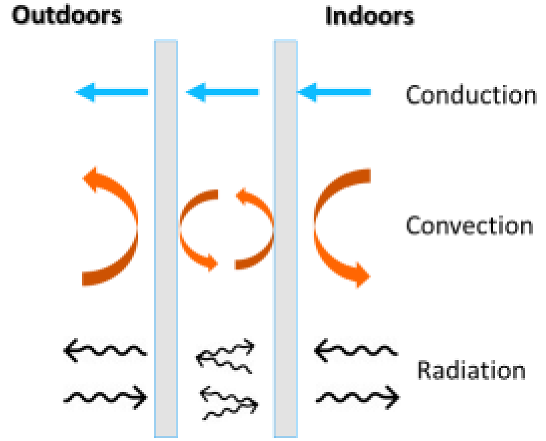
Acknowledgements

PARC	Palo Alto Research Center Early stage technology developer	Stephen Meckler, Gabriel Iftime, Austin Wei, Mahati Chintapalli (PI)
Pilkington, NSG Group	High volume glass manufacturer	David Strickler, Lila Dahal, Kyle Sword, Neil McSporran
Blueshift International Materials	Production scale aerogel manufacturer	Garrett Poe, David Irvin, Alan Sakaguchi, Marisa Snapp-Leo

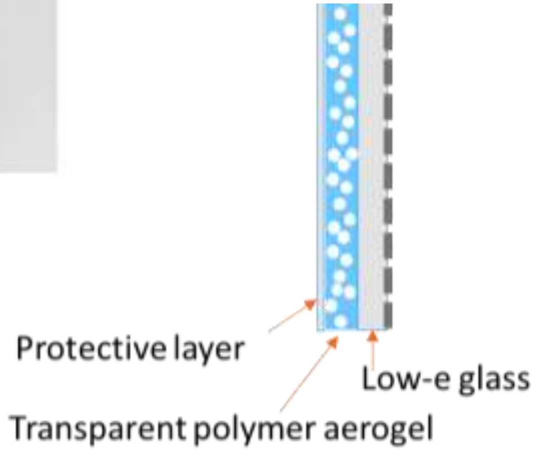
Polymer Aerogel Pane Architecture



Double pane



Proposed pane



Integrate aerogel with commercial pyrolytic low-e glass to alleviate heat loss due to convection, conduction, and radiation

Target Technical Metrics

Our Technology

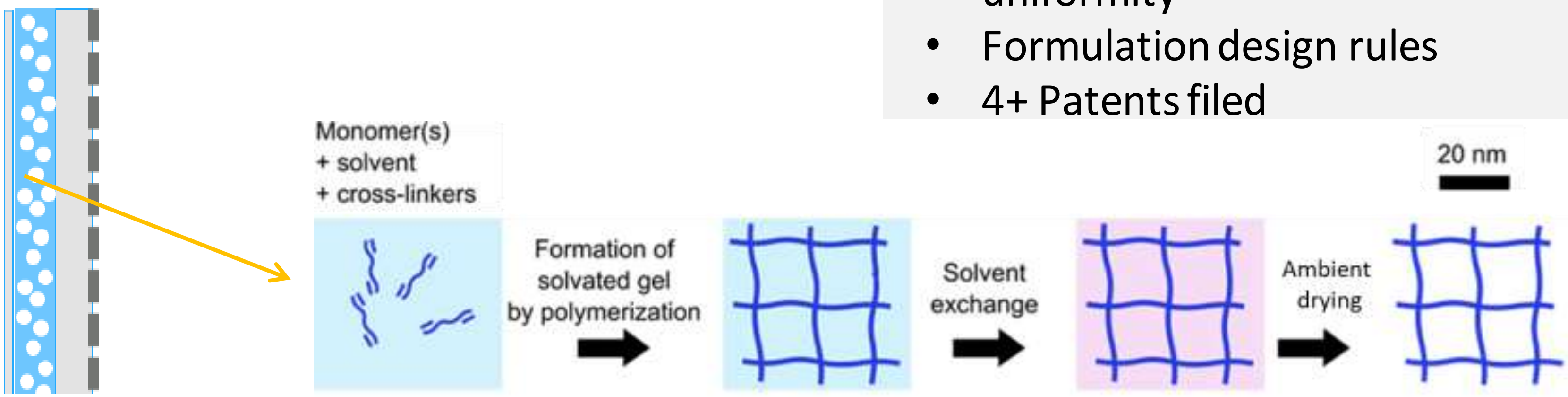
- All polymer aerogel with sub-10 nm pores and porosity > 80%
- Mechanically tough and moisture resistant
- Integrates with existing low-e glass
- Scalable using existing manufacturing
- New windowpane or retrofit

Target Specs

- Thermal conductivity < 0.020 W/mK
- U-factor < 0.4 BTU/F/hr/ft^2
- Haze < 1% (1/8” thick)
- Visible transmittance > 80%
- Durability > 20 years
- Cost < \$10/ ft^2

Core Innovations and IP

- Polymer aerogel window pane
- Methods to control pore size and uniformity
- Formulation design rules
- 4+ Patents filed



Technical Challenge: Simultaneous Transparency and Porosity

Porous polystyrene: Opaque

Dense polystyrene: Optically transparent

Thermal insulation requires high porosity

- Pores > ~20 nm scatter visible light (Rayleigh and Mie)
- Scattering is highly pore size dependent

Scattering Cross section — Pore size

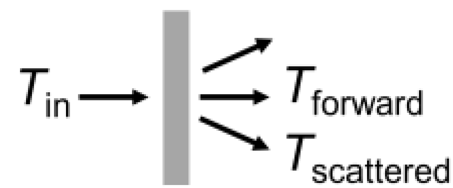
$$\sigma_s = \frac{2\pi^5}{3}\frac{d^6}{\lambda^4}\left(\frac{n^2-1}{n^2+2}\right)^2$$

Silica aerogel with hazy, blue appearance, supercritical CO_2 drying

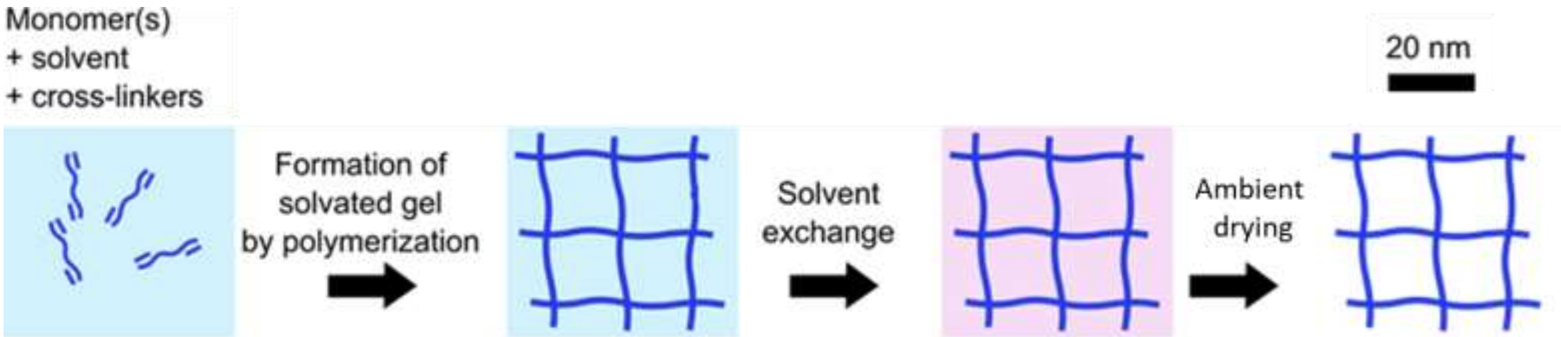
Window applications require:

- High visible transmittance AND
- Low haze (*H*)

$$H = \frac{T_{scattered}}{T_{total}}$$



Fabrication of Transparent Polymer Aerogels By Controlled Radical Polymerization



- All process steps play a role in achieving small pore size at high porosity
- Low thermal conductivity: Solvent in gel turns into porosity upon drying
- Low haze/high transparency: Narrow pore size distribution and small scatterer size is achieved through **controlled radical polymerization**

Mix reactants

Cast resin at 90 °C

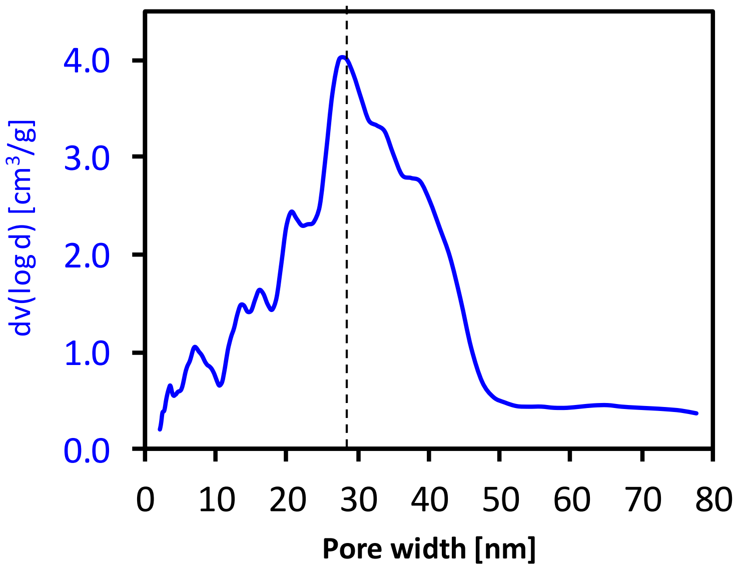
Wet gel

Aerogel on a 1 cm grid

Proof of Concept

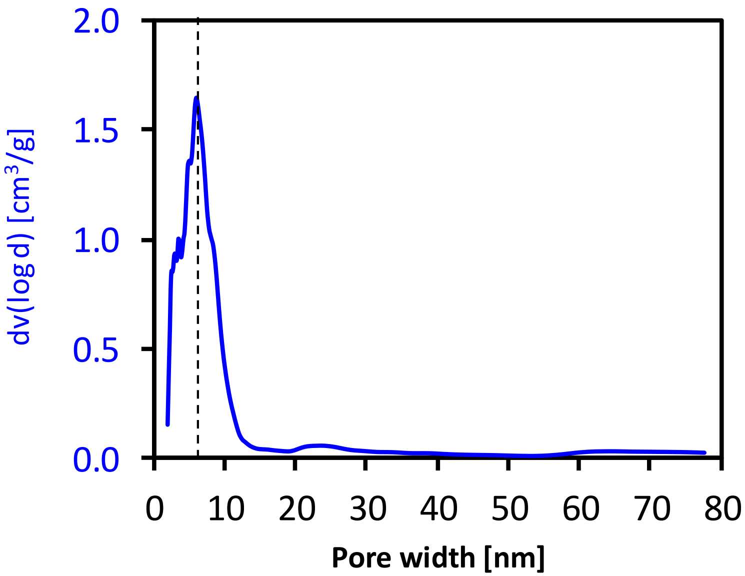
Uncontrolled polymerization

Wet gel: opaque
Aerogel: opaque
Surface area: 830 m^2/g
Porosity: 66 %



Controlled polymerization

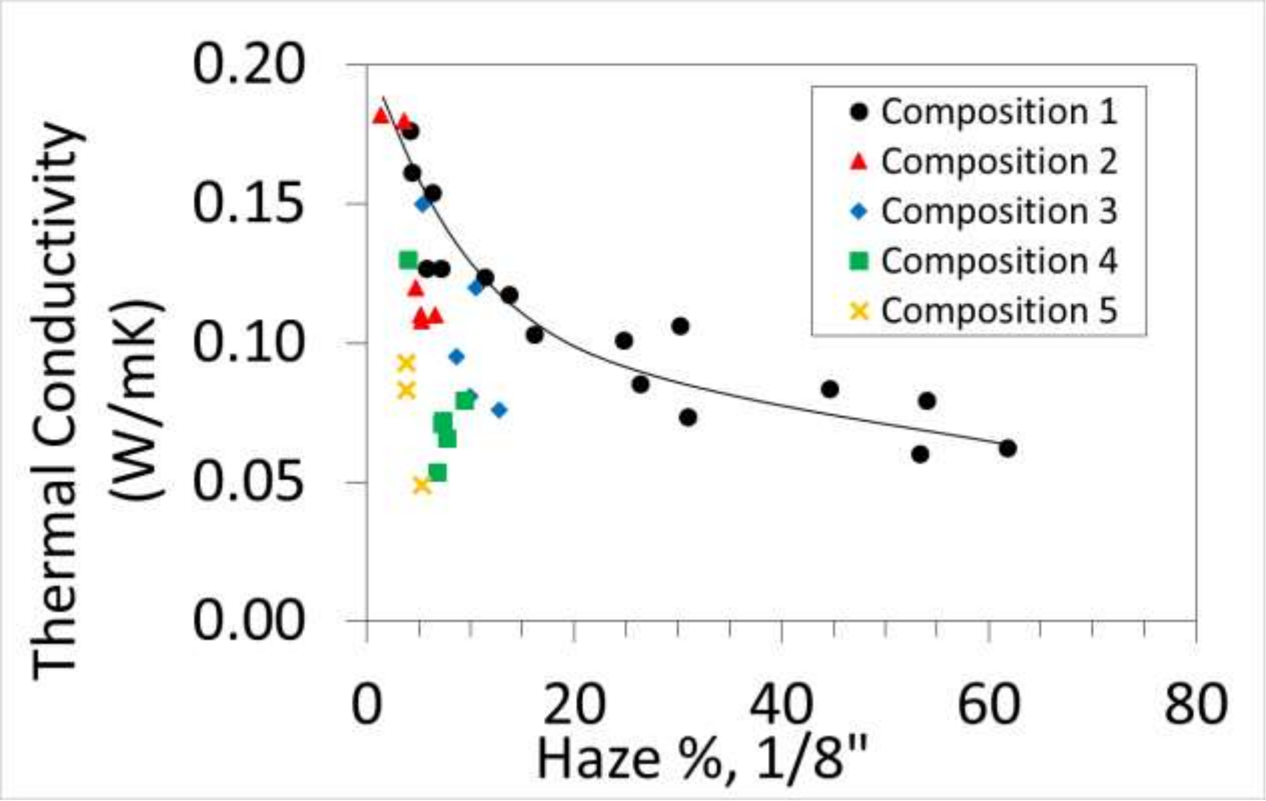
Wet gel: transparent
Aerogel: transparent
Surface Area: 850 m^2/g
Porosity: 42 %



- Controlled polymerization gives transparent, porous materials with ambient drying
- Controlled radical polymerization leads to suppression of large pores

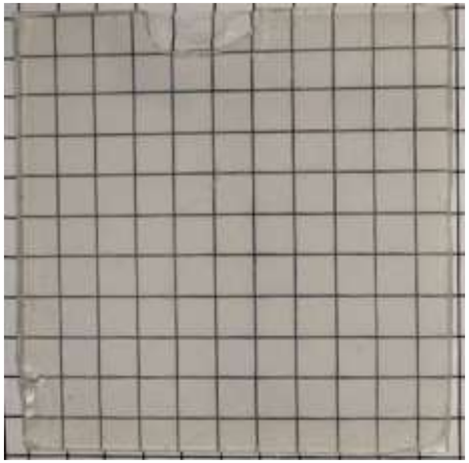
Overcoming Thermal Conductivity-Haze Tradeoff

- Early in the project, we found a thermal conductivity-haze tradeoff
- Can move off of tradeoff by picking precursors to have intrinsically favorable optical and thermal properties



Prototype Performance

Pane prototype at 4x4”,
On low-e glass



Pane performance (from same sample)

- Size: 4 x 4 x 1/8” ambient dried aerogel
- Transmittance = 70 %
- Haze = 7 %
- U-factor = 0.57 BTU/hr/ft^2/^{o}F

- Best lab-scale aerogel performance at 2x2”: 0.07 W/mK, 5 % haze

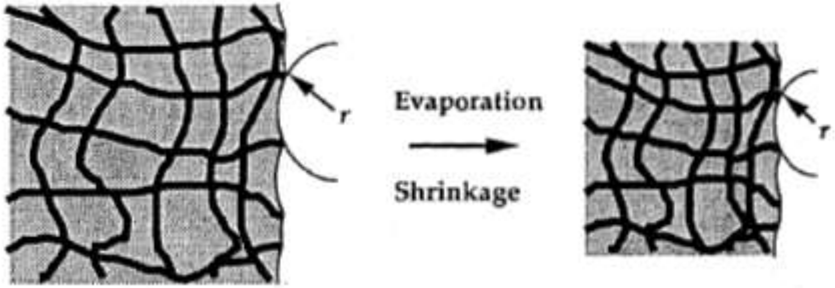
Remaining challenges

- Reduce process cost: increase yield, decrease process time and shrinkage
- Larger size: overcome cracking
- Further decouple pore size and porosity to decrease U-factor and haze

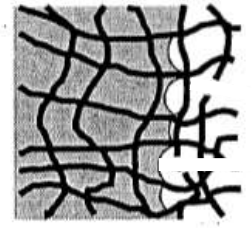
Reducing Process Cost

- Estimated cost is $9-26/ft^2 depending on target vs. near term process conditions
- Solvent-based processing leads to direct and indirect costs
- Main cost drivers:
  - Amount of solvent during solvent exchange → **now minimized**
  - Yield during drying process
  - Shrinkage during drying process

Drying, stage 1:
Gel **shrinks** and becomes more rigid

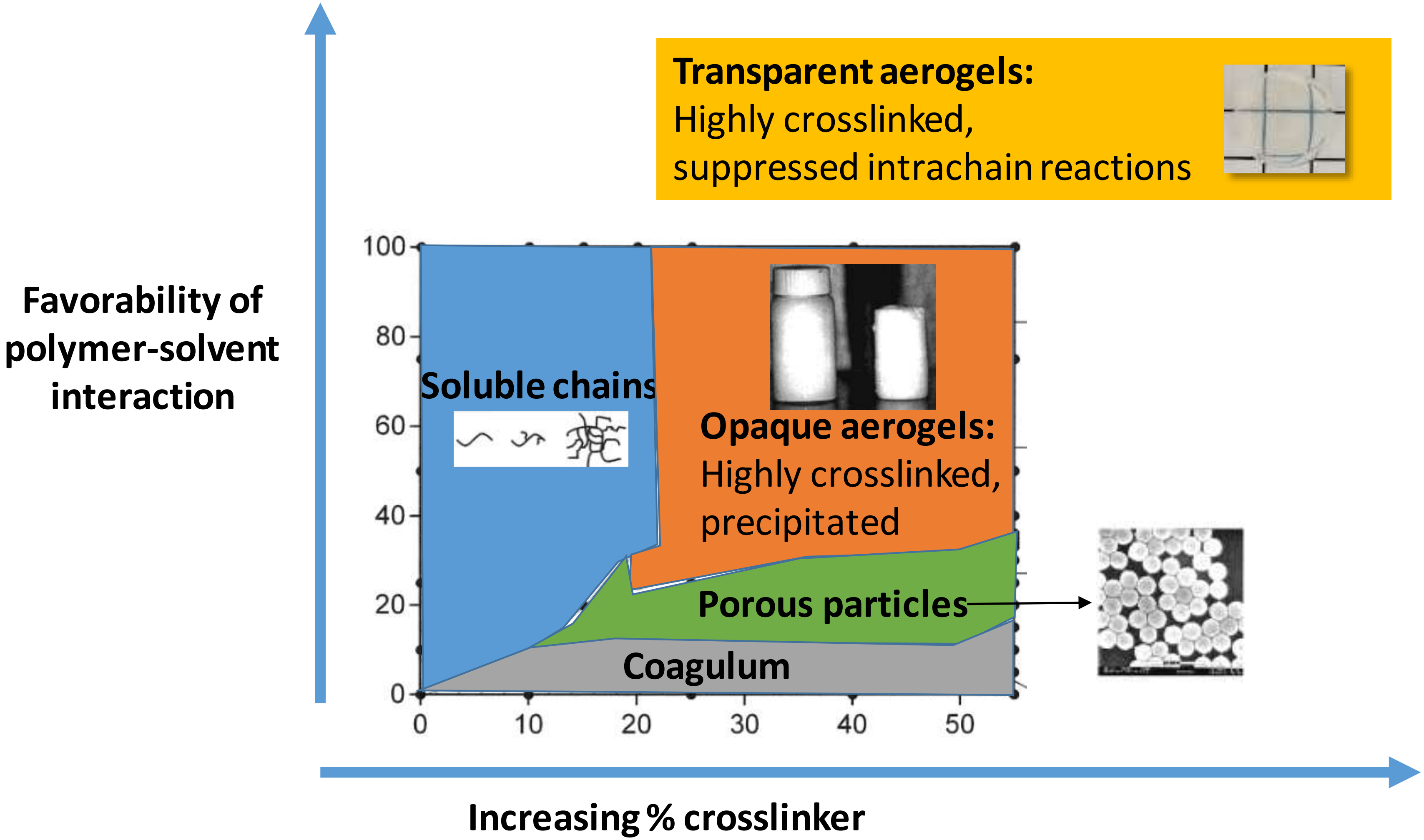


Drying, stage 2: pores empty:
Aerogel is susceptible to **cracking** due to capillary stresses

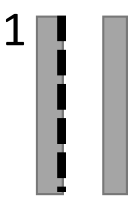


- Solvent-free manufacturing processes are under consideration

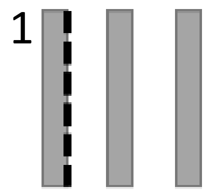
Transparent Polymer Aerogels Represent a New Polymer Aerogel Morphology



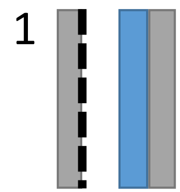
Polymer Aerogels in IGUs Can Enable Thinner Low U-factor Windows



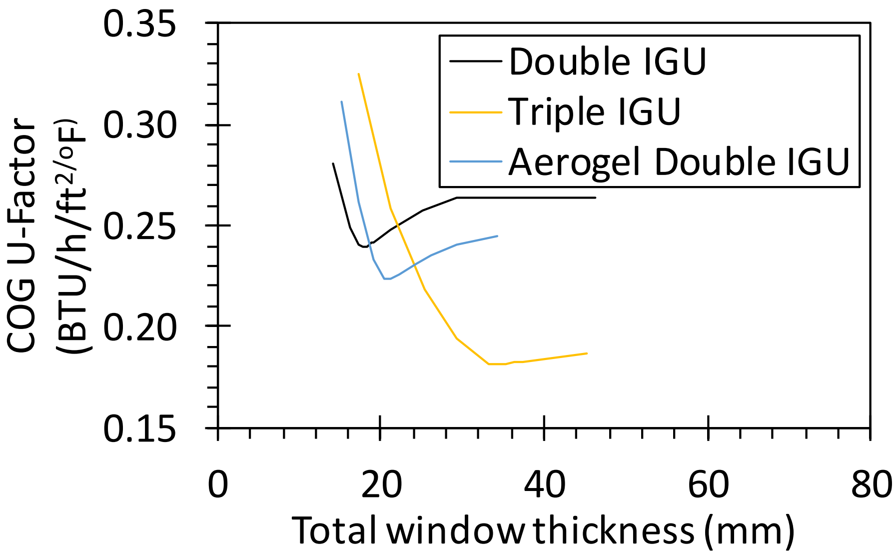
Double IGU:
3 mm silver low-e
90 % Ar gap
3 mm clear glass



Triple IGU:
3 mm silver low-e
90 % Ar gap
3 mm clear glass
90 % Ar gap
3 mm clear glass



Aerogel Double IGU:
3 mm silver low-e
90 % Ar gap
3 mm, 0.07 W/mK aerogel
3 mm clear glass



Aerogel Double IGU Has:

- Lower U-factor than double IGU
- Thinner, and lighter than triple IGU

Modeled using lab scale performance of aerogel

Lessons Learned

- Skylights, storm windows, and daylighting are interesting entry markets for aerogel insulation, as long as there is a long term path to larger markets

Skylights:
Less stringent optical requirements

Storm windows:
Less stringent durability requirements

Daylighting:
Doesn't require aerogel to be a monolith

- Ambient drying is not automatically cheap:
  - At scale, solvent-based processes are expensive, even with commodity organic solvents
  - Low cost requires short process times and small solvent volumes

Project Outputs

- Publication in progress: "*Controlled Radical Polymerization Enables Optically Transparent, High Surface Area Polymer Aerogels*"

- 2 conference presentations:
  - 2018 Gordon Conference on Membranes, Materials, and Processes
  - 2019 American Physical Society March Meeting, Polymer Science

- 4+ patents filed covering the use of polymer aerogels in windows, design guidelines, and controlled polymerization methods

- **We are actively seeking:**
  - **Polymer aerogel manufacturing partner**
  - **Potential technology licensees**
  - **Follow-on funding to explore solvent-free approaches**

Project Next Steps

- Explore **solvent-free manufacturing approaches** to:
  - Reduce process costs related to solvent and solvent handling
  - Reduce process costs due to shrinkage by eliminating capillary forces in drying
  - Reduce shrinkage to decrease U-factor

De-risk solvent-free manufacturing
0.5 -1 yr, ~200k
Reach target performance of 1% haze, U-factor 0.4 (eng)

→

Field Prototype

1-2 yr, ~500k
Produce and test prototypes >= 12” and validate manufacturing cost

- Explore other applications for polymer aerogels

Bibliography

Chintapalli, Mahati. 2019. All-polymer transparent thermal barriers. Presented at the 2019 Buildings XIV Conference, Clearwater Beach, Florida, December 9 - 12.

Brinker, *Sol-Gel Science*, 1990

Chart adapted from: Downey, Stöver, *et al. Macromolecules* 2001

QUESTIONS?

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Workshop 8
DOE Building Envelope Research Projects on Fenestration and Grid Interaction

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Aerogel Insulated Glazing Unit

Acknowledgements

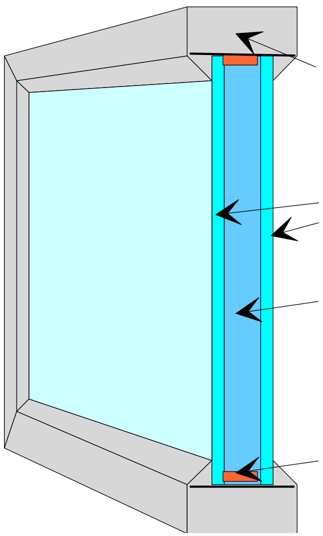
- LBNL – characterization and modeling (Charlie Curcija, Luis Fernandez, Stephen Selkowitz)
  - Modeled the performance, determined the optical properties and TCs of A-IGUs, and prepared a spreadsheet to determine U-factors from thermal conductivities.
- NREL – long term stability testing (Robert Tenent)
  - Solar radiation stability
    - Exposed aerogels to solar radiation for 5048 hours
    - Monitored changes in water contact angle and UV-Vis-NIR spectra of samples after exposure.

- RTI – Mike Osbourne and Jackelyn Vander Veer
  - RTI conducted market research to explore how Aspen's technology resonates within the window restoration and new construction window markets.

Objectives/Goals

Objective

- Develop a thin profile window pane that can be installed in the existing frame to improve energy efficiency of single pane windows.
- Silica aerogels are one of the best transparent insulation materials known and offer an approach to make energy efficient windows.



Our Solution

- Develop a cost effective process to form transparent silica aerogel between two panes of glass.

Project Goals

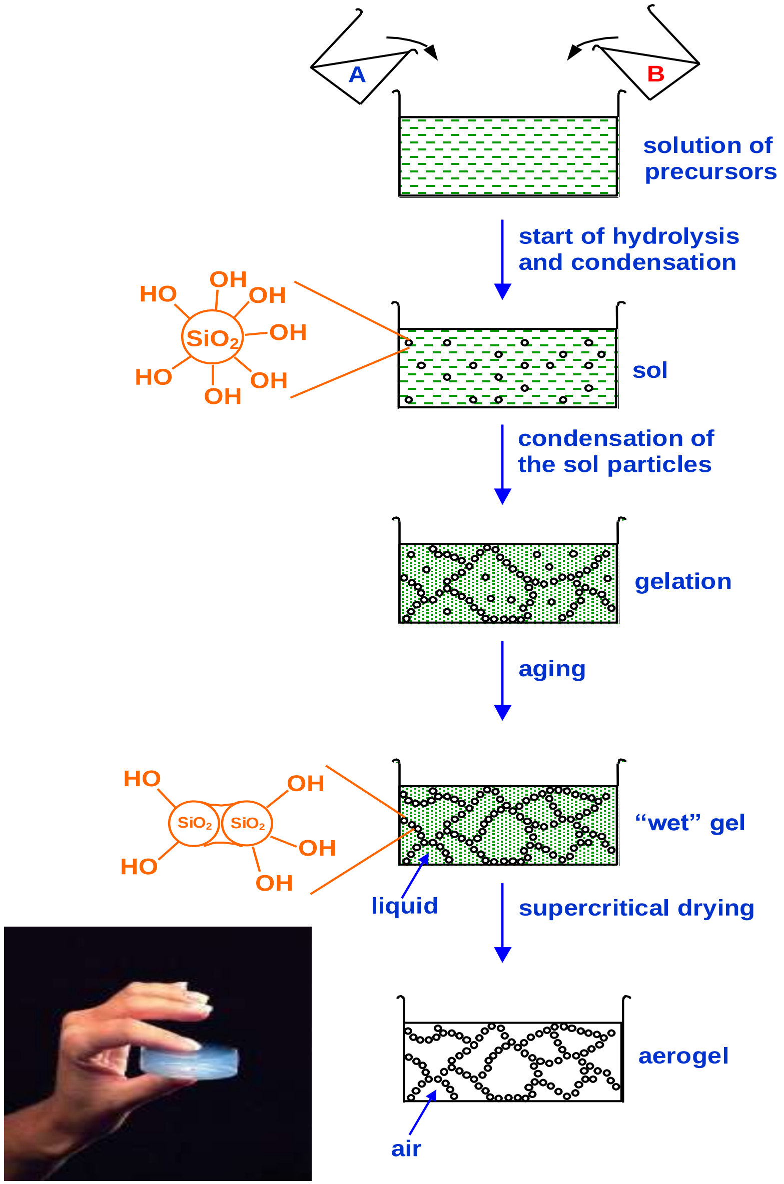
- Reduce cost of manufacturing transparent monolithic aerogels (< $10/sq. ft.).
- Increase product throughput.
- Shorten preparation and drying times (hrs. vs. days).
- Eliminate stresses created during supercritical drying.
- Eliminate handling of monolithic gel and aerogel panels.

Target Technical Metrics

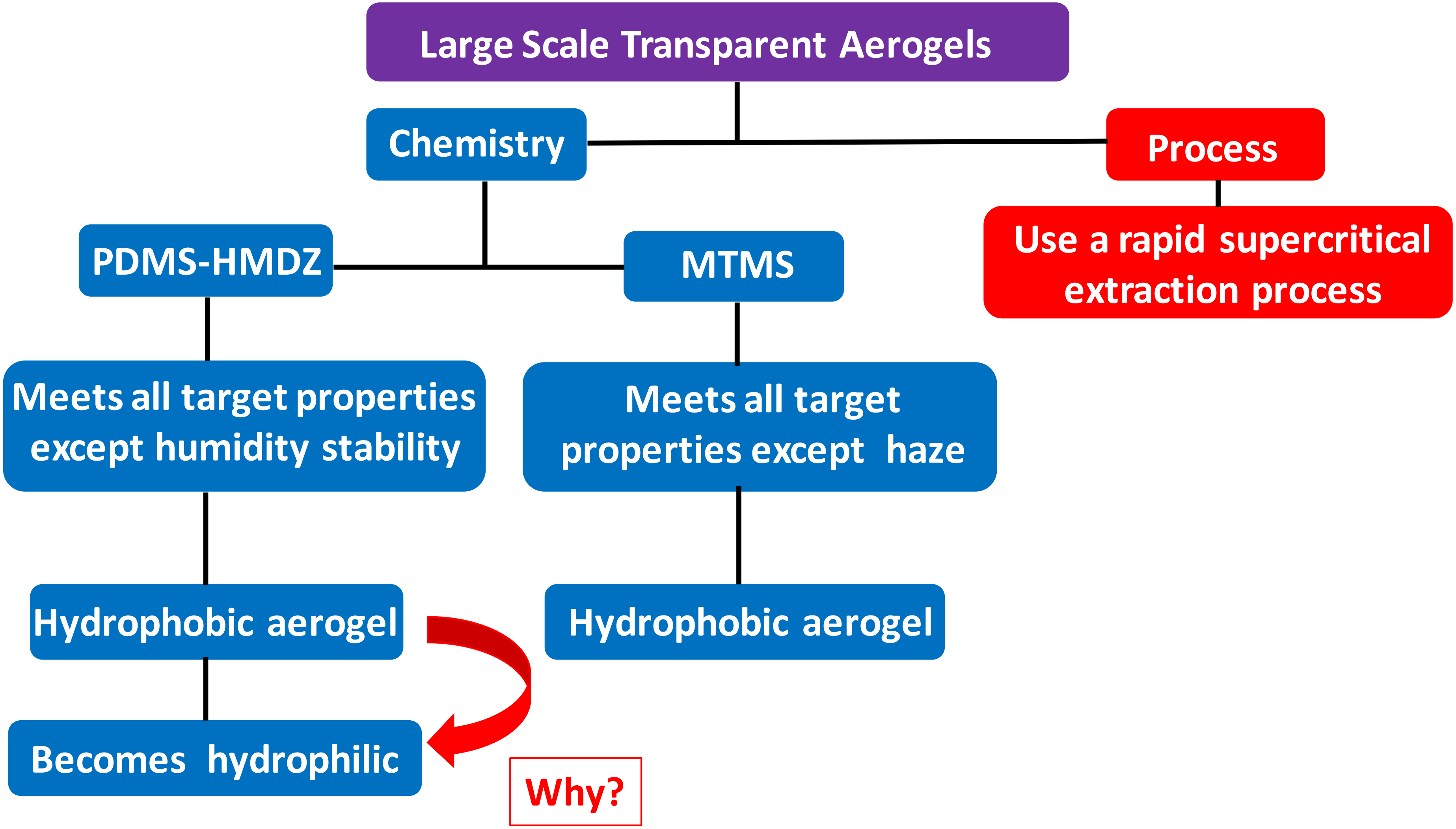
	Prototype 4
Quarter Due	12
Size/description	1' x 1' ¼" total thickness (aerogel dried through the thin dimension)
Property	**Metric**
U (BTU/sf/F/hr)	<0.4
Haze	<1%
Visible light transmission (T_{vis})	>80%
Color rendering index (R_a)	>0.9
Humidity	Pass
Thermal Conductivity (TC), (mW/m-K)	< 14
Temperature cycling	Pass extensive thermal test
UV stability	Pass
Uniformity	Pass
Manufacturing Cost	Path to <$10/sq. ft.

Technical Results

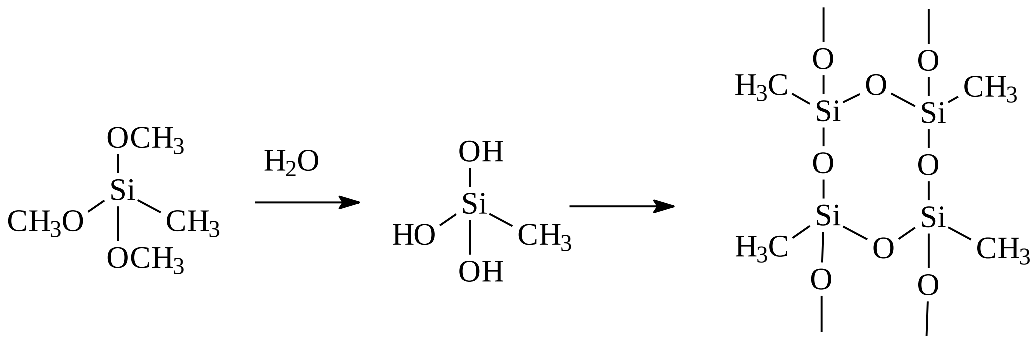
- Silica aerogels are nanoporous solids that are prepared by sol-gel methods.
- Add and dissolve monomers in the solvent (e.g., ethanol).
- Add polymerization catalysts to catalyze gelation of the sol.
- The aging step strengthens the gel.
- Extract solvents at supercritical conditions to eliminate the vapor-liquid interface and capillary pressure that cause the gel structure to shrink during drying.



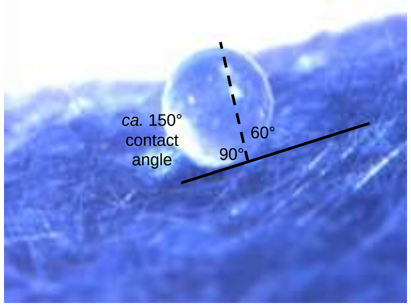
Technical Results



- MTMS aerogels are prepared from methyltrimethoxysilane

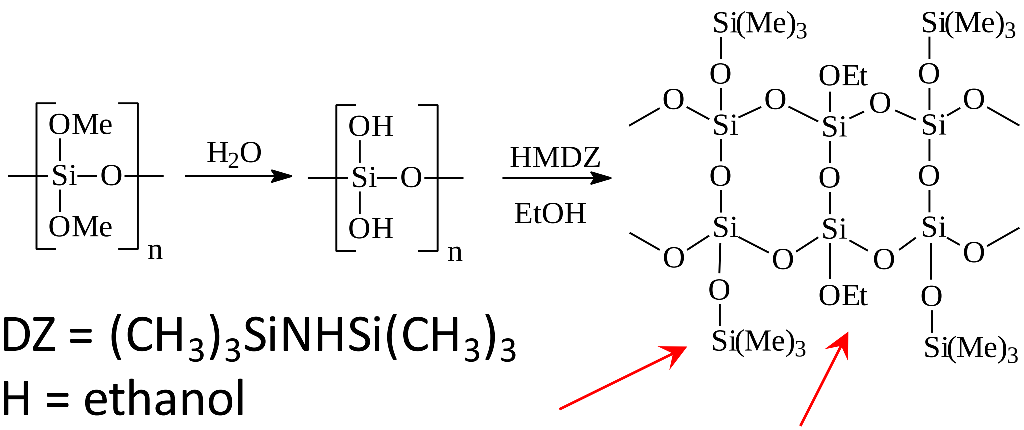


Hydrophobic



Water beads up on surface

- PDMS aerogels are prepared from polydimethoxysilane.



Hydrophobic

⬇

Becomes hydrophilic

$HMDZ = (CH_3)_3SiNHSi(CH_3)_3$

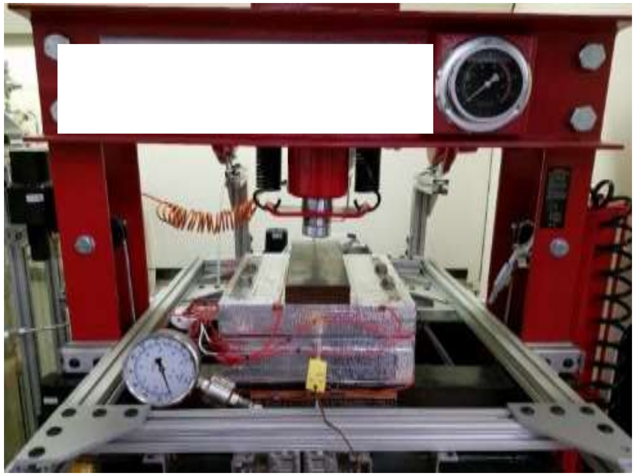
EtOH = ethanol

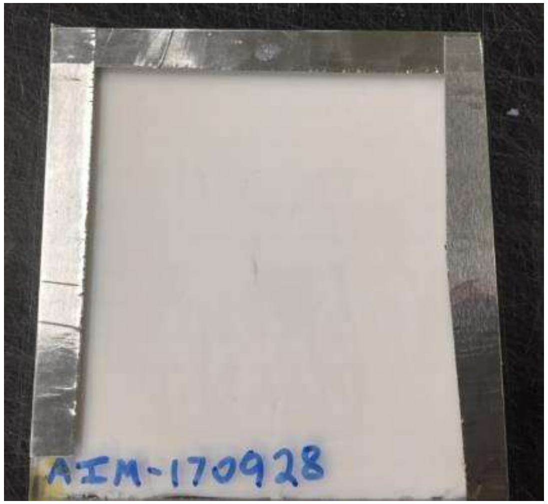
Both $-Si(Me)_3$ and -OEt groups contribute to hydrophobicity.

Need high concentration of HMDZ hydrophobe to replace ethoxy groups to have durable hydrophobicity.

Technical Results

- We initially used a rapid supercritical extraction (RSCE) process designed to speed-up production of aerogels.
- The RSCE process is very similar to injection molding processes used to manufacture certain types of plastics.
- The sol is injected into a mold at supercritical conditions, gelled, aged, depressurized, and cooled to obtain the aerogel.
- However, the best aerogels we made by this process were opaque.
- **We changed our approach since this process was not producing transparent aerogels.**





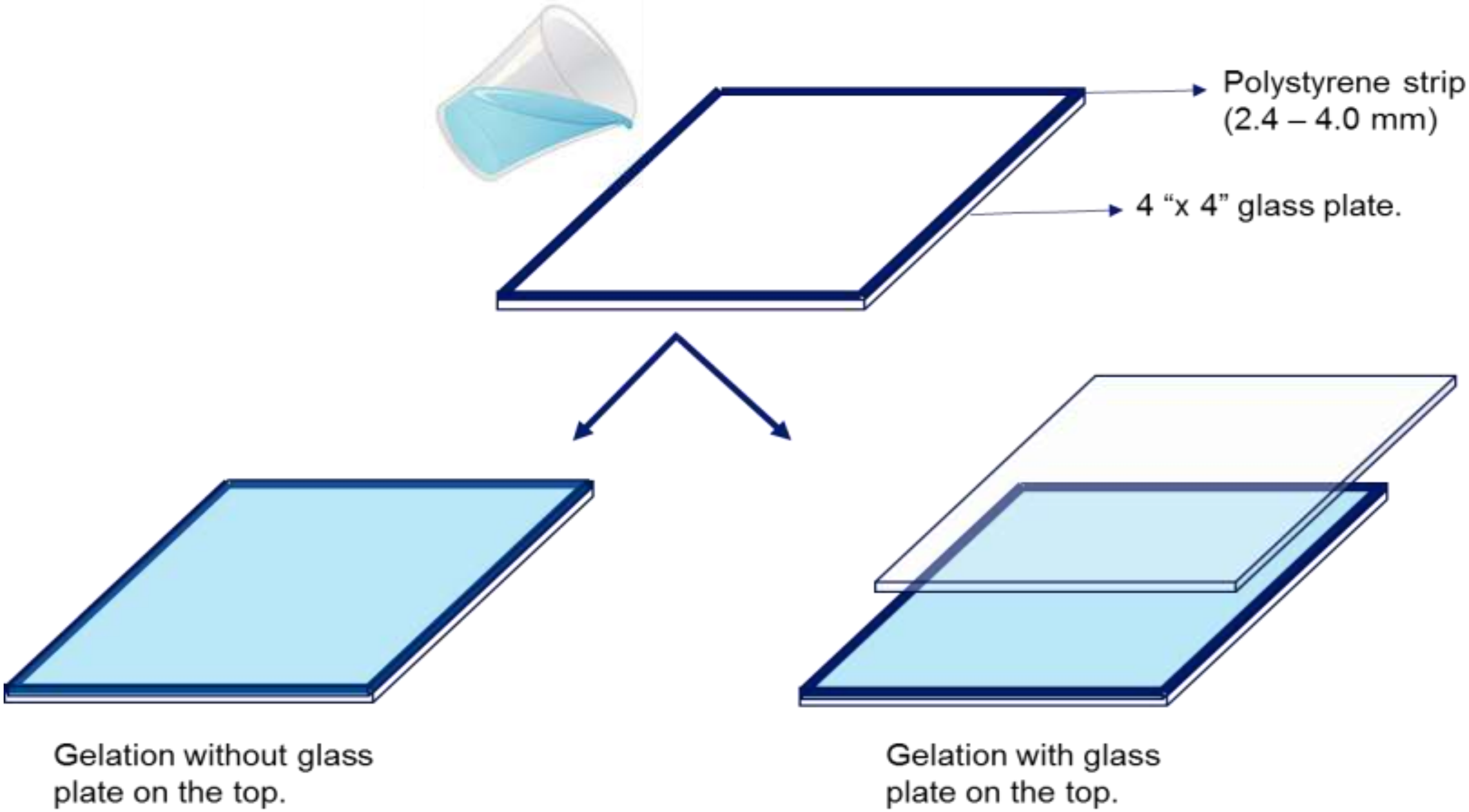
Monolithic opaque aerogel

Technical Results

- 4” x 4” Prototype was prepared by forming and supercritically drying the gel between two panes of glass.
- Required drying from the edges of the pane.
- Haze was ~1% and thermal conductivity was 13 mW/mK for a 3 mm thick aerogel.
- Indicated that it is possible to produce an aerogel insulated pane that meets project targets.
- Drying through the edges was not a viable approach for larger aerogel insulated panes.

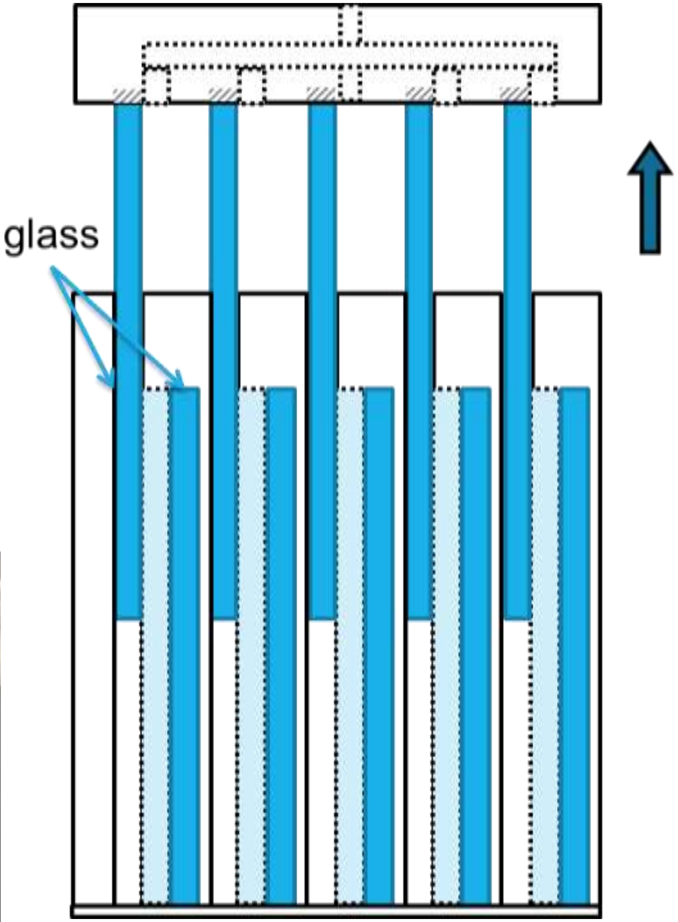
Technical Results

- We changed our approach to dry the gel through the thin dimension by casting the sol on one sheet of glass.



Technical Results

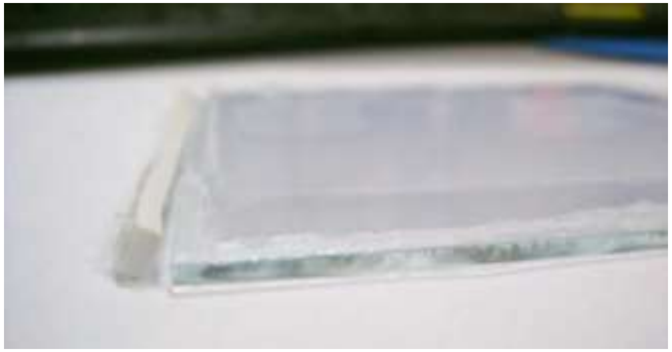
- We designed a multi-pane mold to form the gel between two panes of glass.
- The mold facilitated removal of one pane of glass.
- After gelation and aging, one pane was removed for supercritical drying to form the aerogel.
- We succeeded in preparing 5 4” x 4” panes simultaneously.
- Had problems scaling this approach to larger sizes.



Technical Results

- 4” x 4” Gels dried through the thin dimension.

Cast between two glass panes.
Removed one pane for drying.



Cast on one pane

- Haze is ~1% higher when gel is dried through the thin dimension.
- Haze was similar for casting on one glass pane or between glass panes.

Gel casting	Thickness (mm)	% Haze	% Light Transmittance	% Diffuse Luminous Transmittance
On one glass panes	3.1	2.34	90.65	2.36
Between two glass panes	3.2	2.28	90.33	2.28

Technical Results

Large Scale Transparent Aerogels

Chemistry

Process

Dry aerogel through thin dimension

One Glass Pane

Keep surface clean

Two Glass Panes

Remove glass pane after gelation

Multi-pane mold

Goal – crack-free 12” x 12” A-IGUs

Technical Results

- Crack-free MTMS aerogels have durable hydrophobicity and are stable to moisture exposure.

8" x 8" MTMS aerogel

The haze before and after exposure to 95% RH at 49 °C.

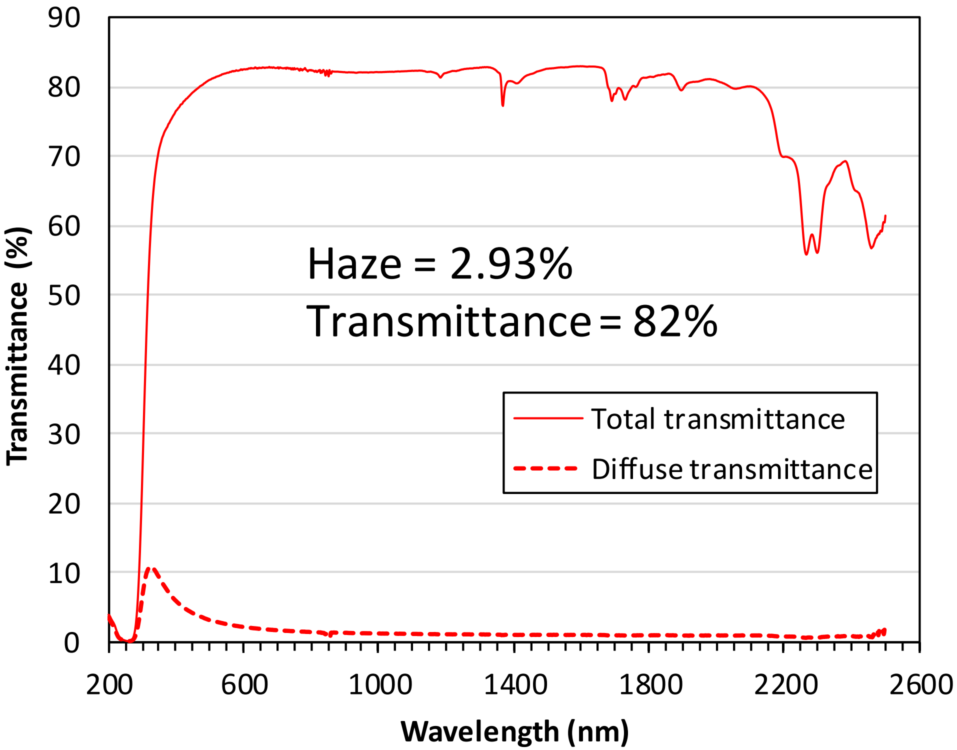
Sample #	Glass Type	% Haze Before	% Haze After	% Change
1	Clear/Clear	3.97	3.85	-3.02

- The haze for MTMS aerogels was higher than 3% and did not meet the haze criteria.

Technical Results

- Crack-free PDMS – HMDZ aerogels.
- The sol was cast on one pane of glass, dried through the thin dimension, and sandwiched between two 8” x 8” glass panes.

Haze < 3%



Technical Results

- Prototype 12” x 12” panes using PDMS-HMDZ formulation.
- Due to aerogel shrinkage and adhesion of the gel to the glass we were not able to prepare crack free 12” x 12” aerogel panes on a routine basis.

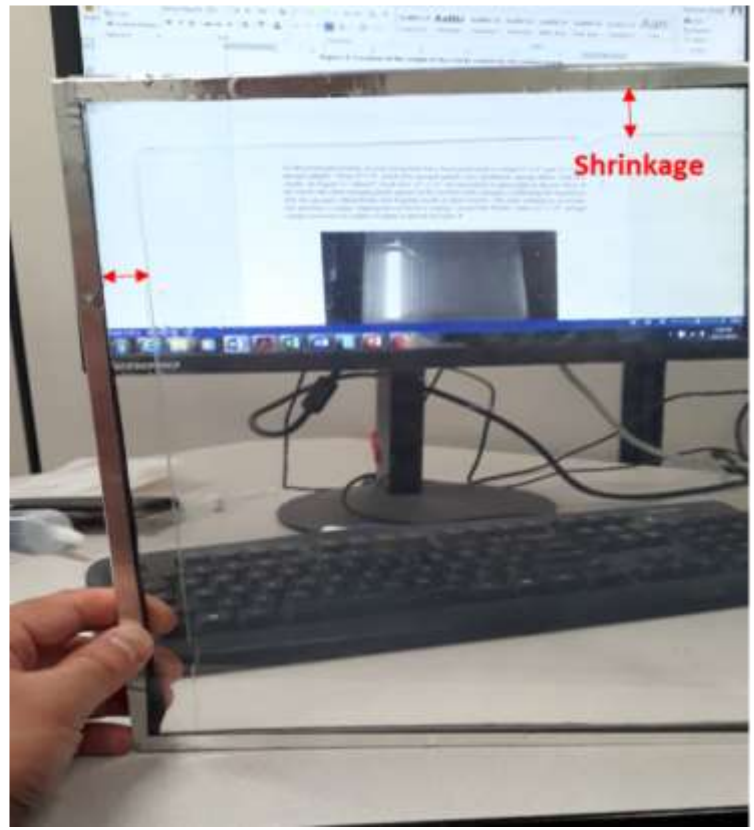
Aged 2 days (0.75% NH_3, 68 °C)

Aged 1 month
Polystyrene spacer does not survive supercritical CO_2.

Technical Results

- Used polystyrene spacer and polyisobutylene adhesive.
- Gel did not adhere to the glass and shrank during aging.
- Most of the shrinkage (70%) occurred during aging.

Aged for 1 month



Lessons Learned

- It is possible to produce a transparent aerogel that has a haze of 1% and a thermal conductivity of ~13 mW/mK but scale-up of the process presents unique challenges.
- It is important to produce aerogels with clean/smooth surfaces to minimize haze.
- Adhesion of the aerogel to the glass pane is not recommended and can cause the gel to crack during drying.
- MTMS gels do not shrink during drying and the resulting aerogels are hydrophobic but have higher haze.
- Hydrophobic aerogels are stable and are expected to have long lifetimes.
- Hydrophilic aerogels need to be protected from exposure to moisture since they are susceptible to stress corrosion cracking.

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Wendell E. Rhine, Redouane Begag, Roxana Trifu, Kathryn deKrafft, Wenting Dong, Irene Melnikova, and Shannon White. 2019. Aerogel Insulated Glazing Unit. Presented at the 2019 Buildings XIV Conference, Clearwater Beach, Florida, December 8.

J.F. POCO, P.R. CORONADO, R.W. PEKALA and L.W. HRUBESH, "RAPID SUPERCRITICAL EXTRACTION PROCESS FOR THE PRODUCTION OF SILICA AEROGELS," MRS Symp. Proc. Vol. **431**, 297 (1996)

QUESTIONS?

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Seminar 32 – Energy Efficient Design for Large Buildings

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Thermally Insulating and Optically Clear Mesoporous Silica Monoliths

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  - Prof. Laurent Pilon (PI)
    - Heat transfer, optics, interfacial phenomena
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    - Material science, sol-gel processes
  - Prof. Yongjie Hu
    - Nanoscale heat transfer
  - Prof. Sarah Tolbert
    - Architecture and synthesis of nanomaterials
- Participants
  - Pilon's group
    - Dr. Michal Marszewski, Tiphaine Galy
  - Dunn's group
    - Patricia McNeil, Maggie Fox
  - Hu's group
    - Zihao Qin
  - Tolbert's group
    - Sophia King, Natalie Kashanchi
- Consultant: Hidden Point Consulting
  - Dr. Peter Bihuniak
- Industry partner
  - Cardinal (Keith Burrows) and NSG


Prof. Pilon


Prof. Dunn


Prof. Hu


Prof. Tolbert


Dr. Marszewski


Tiphaine Galy


Patricia McNeil


Maggie Fox

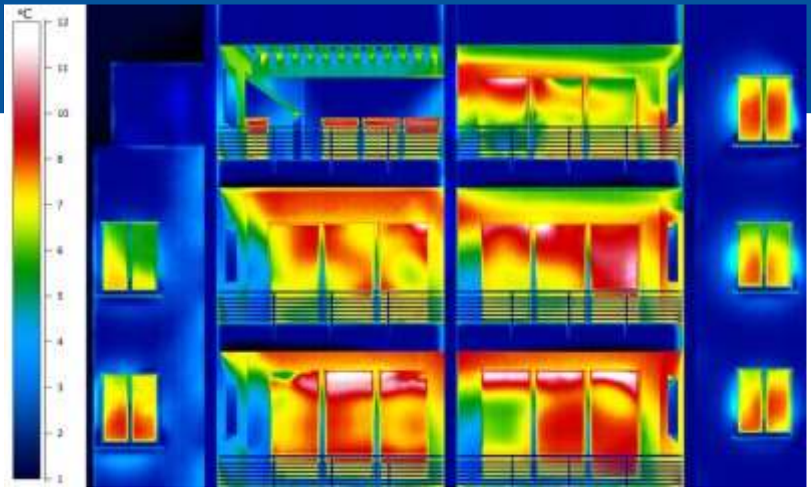

Zihao Qin


Sophia King


Natalie Kashanchi


Peter Bihuniak

Introduction



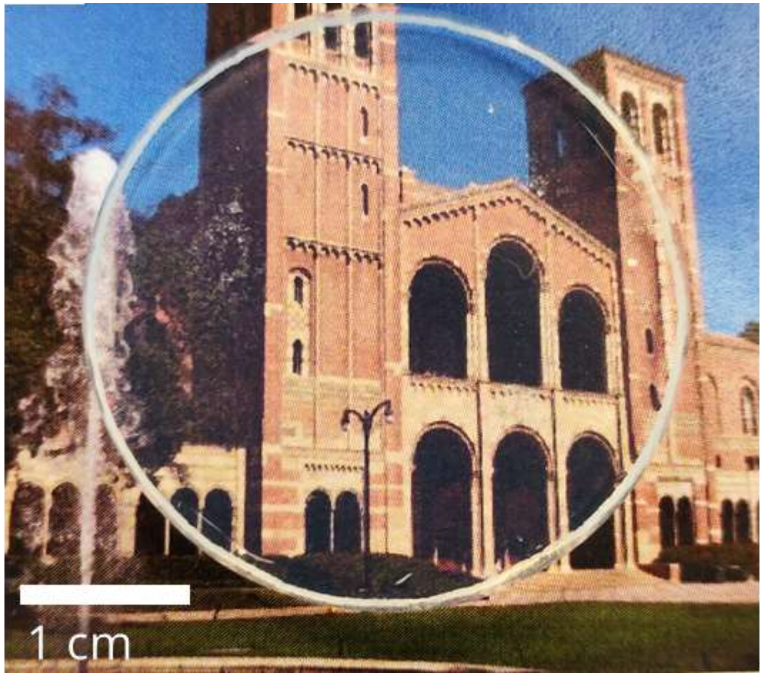
- Market needs
  - A large stock of single-pane windows remains in the U.S.
  - Occupant discomfort due to water condensation
  - New regulations and opportunities
    - Zero net energy buildings
    - LEED certification
- Technical approach: 2 synthesis methods
  - Synthesize of aerogel slabs with controlled pore size (< 20 nm) near ambient conditions
- Target market/implementation scenario
  - Retrofitting of new buildings
  - US commercial buildings: 4.6 M ft^2 of window
  - Eliminate needs for triple pane windows

Double-pane windows with silica aerogel*

Aerogel is translucent not transparent!

Our innovation

Ambigel slabs
1”x1.4” and 1 mm thick
Porosity: 92%, pore size < 20 nm
k < 0.03 W/mK, transmittance > 85%,
Haze < 2 %, Hydrophobic, flexible

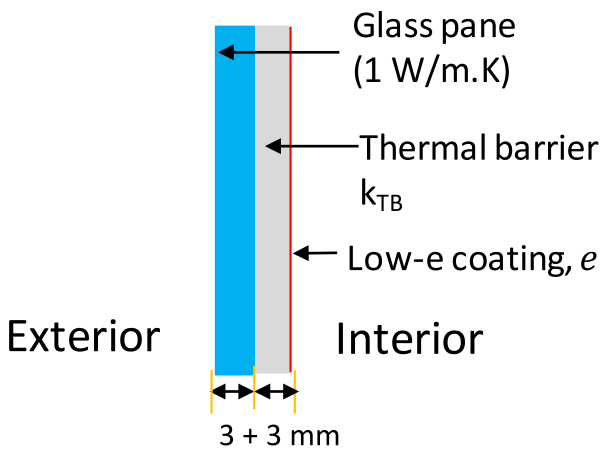


Nanoparticle-based slabs
Diameter: 1.7”, thickness: 3–4 mm
Porosity: 50%, pore size < 10 nm
k ~ 0.1 W/mK, *transmittance > 90 %,*
haze < 3%

Target Technical Metrics

- End of project goals: thermal barrier material
  - Thickness = 3 mm
  - Thermal conductivity < 0.03 W/m.K
  - Optical: haze < 1%
  - visible light transmission T > 90%
  - U-value < 0.4 BTU/sqft.hr.^{o}F

SHIELD design



- Deployment
  - Use readily available materials = easy supply chain
  - Compatible with low-e coating deposition processes
  - Easy bonding to single glass pane
  - Could also be seamlessly integrated in double pane glass window

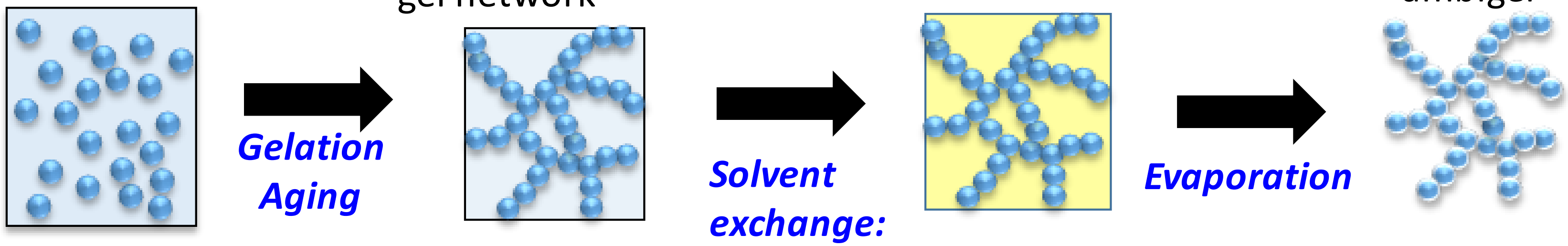
Novel ambigel slabs

- Process feature: at room temperature and atmospheric pressure

TEOS and MTES precursors are mixed

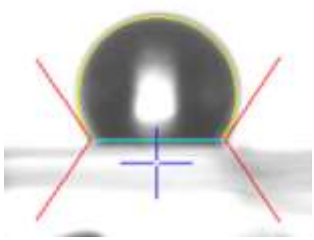
Precursors form porous gel network

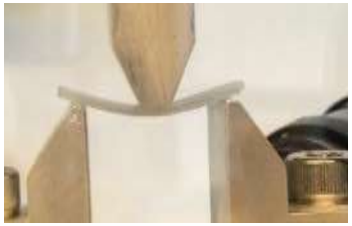
Transparent ambigel



1. Acetone, 2. TMCS treatment, 3. Heptane

- Intellectual property
  - PCT/US2019/39019, June 25, 2019
- Performance
  - Porosity 70-92%, pores < 20 nm
  - Transmittance > 85%, haze <2%
  - k < 0.03 W/m.K
  - Hydrophobic
  - Flexible



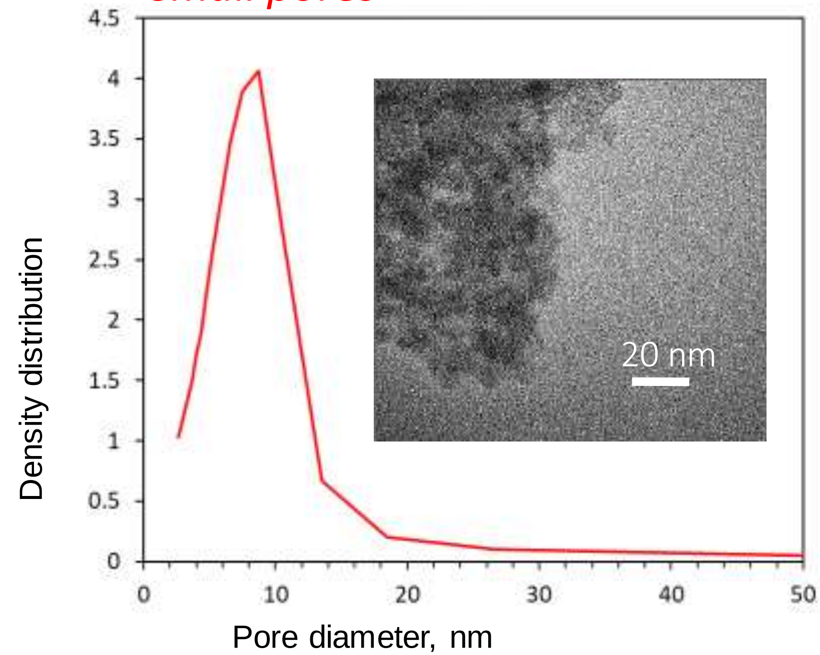


- Current challenges
  - Duration of process (5-7 days)
    - Reduce to 1 day in past 6 months
  - Scaling up the process
  - Cracking of large and thick samples
    - Cause by handling or uneven drying
  - Cost of chemical

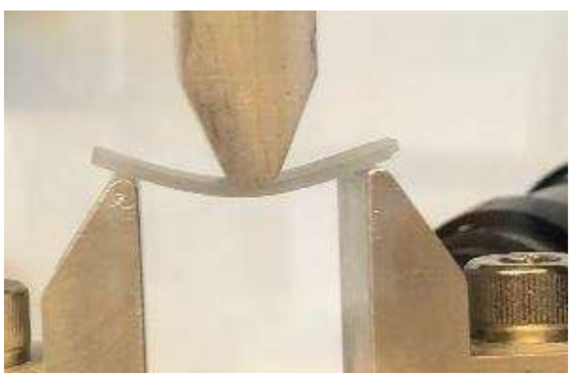
Novel ambigel slabs

transparent

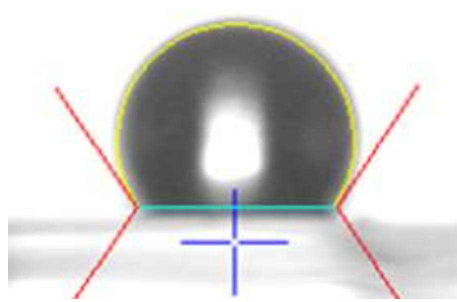
Small pores



flexible



hydrophobic



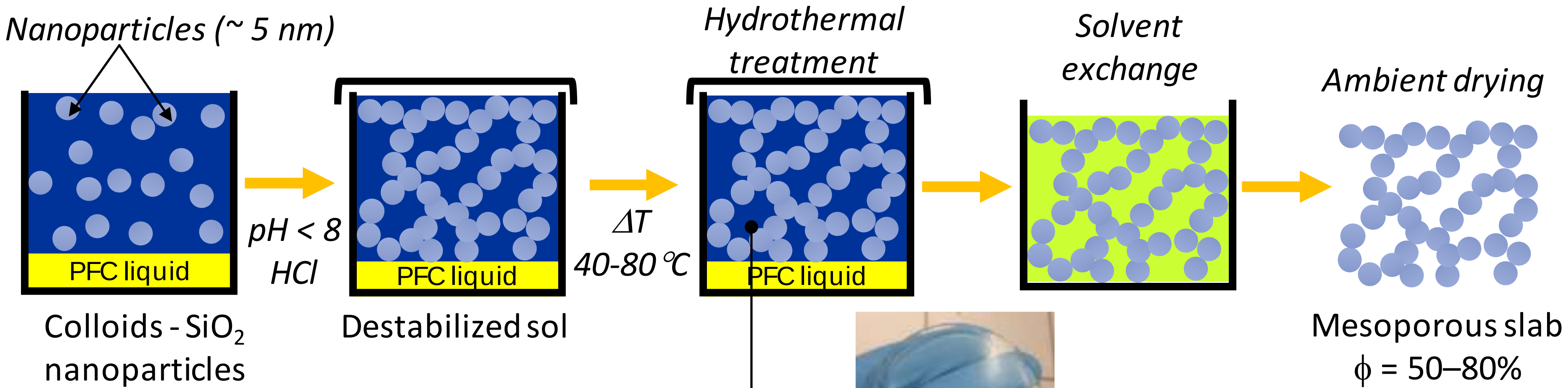
Contact angle = 123°

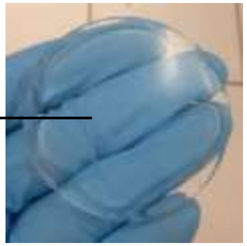
Attributes

- 1–3 mm thick
- Porosity: 92%
- pore size < 20 nm
- k < 0.025 W/mK
- Transmittance > 90%
- Haze < 2 %

Nanoparticle-based mesoporous slabs

- Process feature: at room temperature and atmospheric pressure

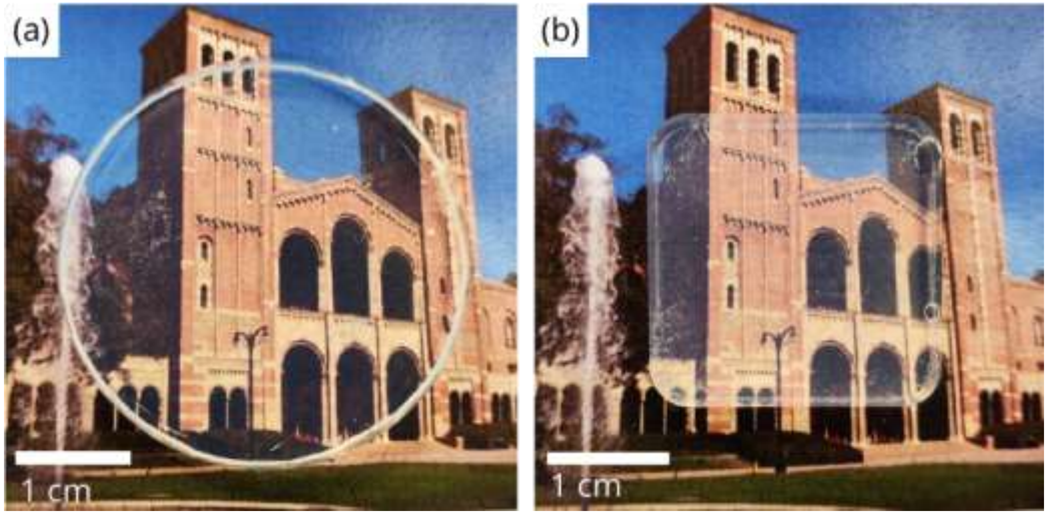




- Intellectual property
  - PCT/US2019/39019, June 25, 2019
- Performance
  - Porosity 50-81%, pores < 25 nm
  - Transmittance > 80%, haze < 10%
  - k < 0.07 W/m.K
- Benefits
  - Gel can be handled by hand and cut to desired shape

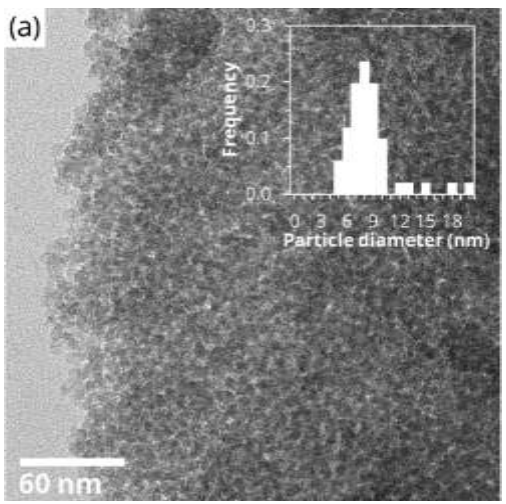
- Current challenges
  - Duration of process (5-7 days)
  - Scaling up the process
  - Cracking of large and thick samples
  - Increase porosity while keeping pores small

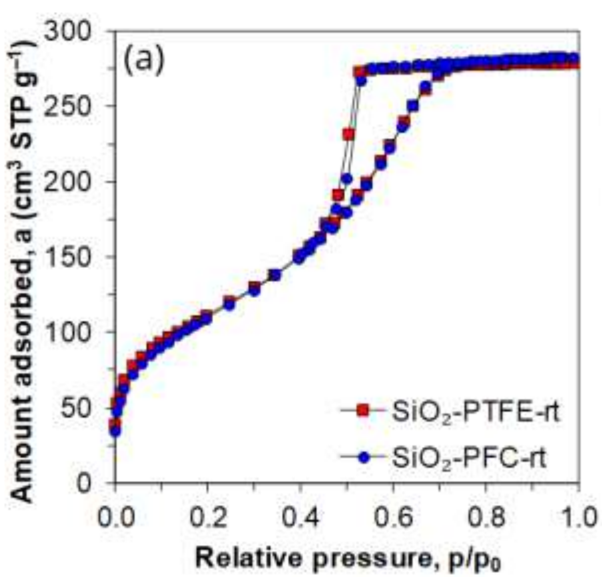
Nanoparticle-based mesoporous slabs*

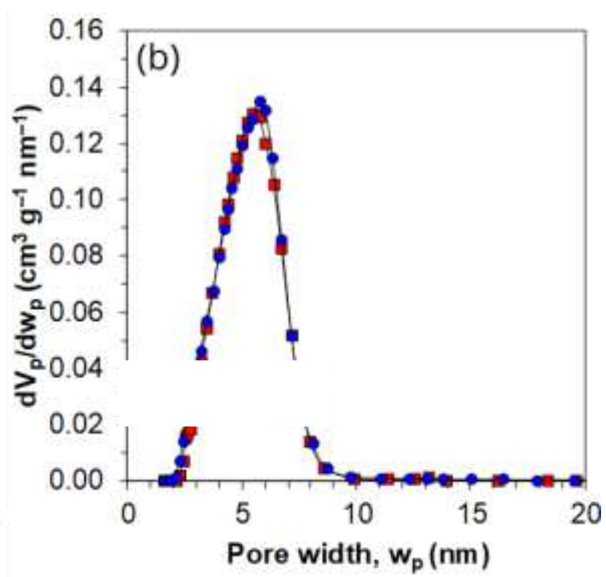


Attributes

- 1–6 mm thick
- 2–10 cm in size
- Porosity: 50–80%
- Pore size < 20 nm
- k = 0.07–0.16 W/mK
- Transmittance > 90%
- Haze < 3 %

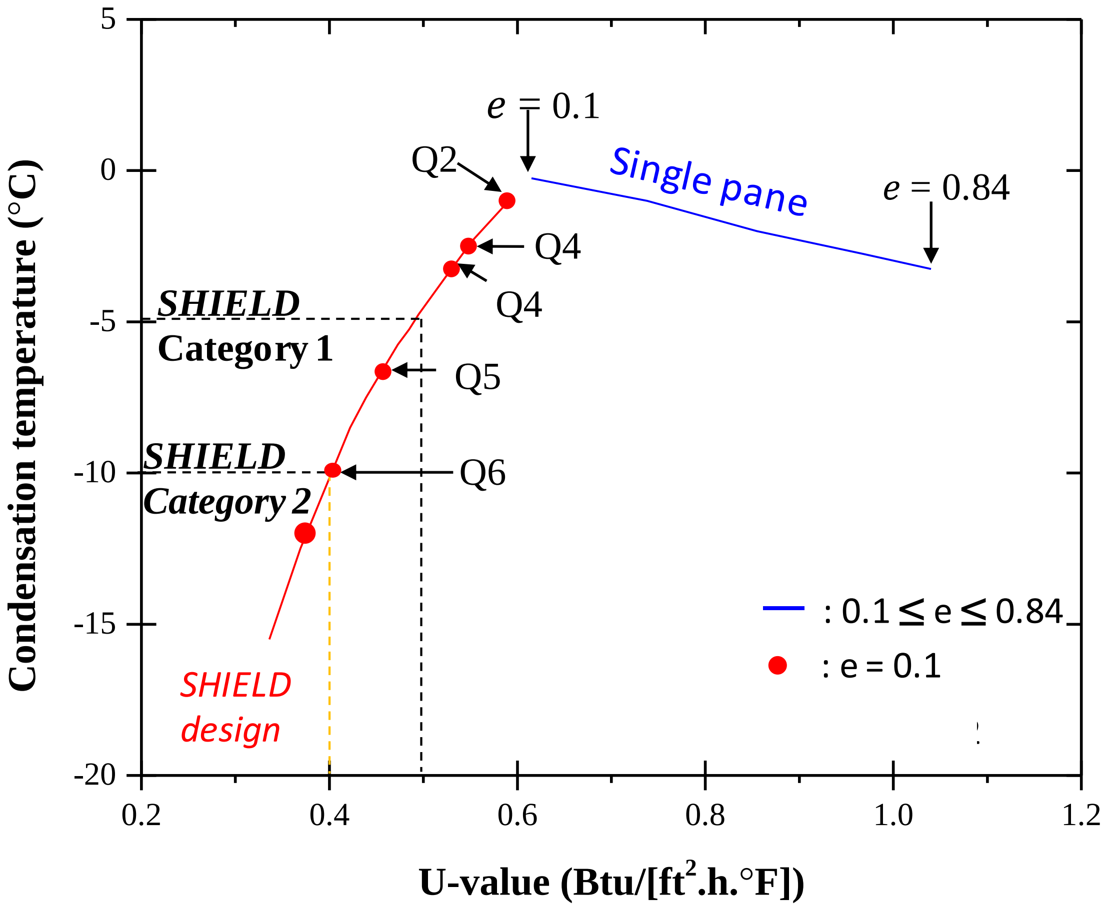




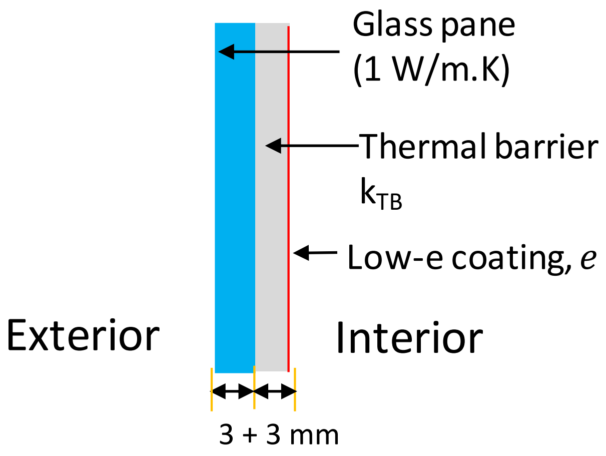


Progress towards SHIELD program goals

- Simulated SHIELD design performance
  - Based on ambigel properties measured for different quarters



SHIELD design



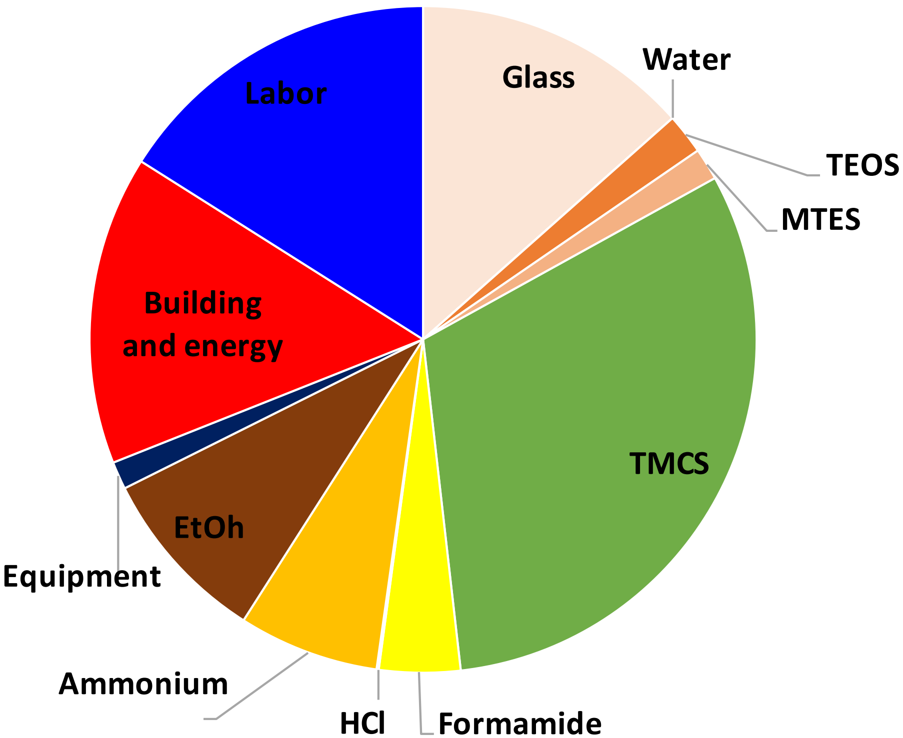
If integrated in IGU

U-value = 0.22 Btu/ft^2.h.F

Cond. temp.= -70 ^{o}C

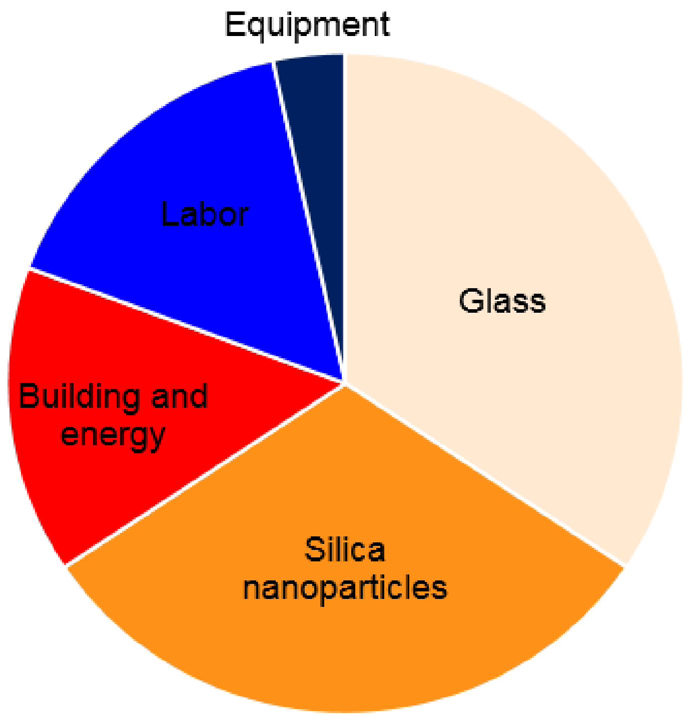
Cost breakdown

- Ambigel
  - Porosity 85%
  - **Assuming 8 hr process**
  - Total cost: **$9.67/ft²**



TMCS is the cost driver of ambigel slabs

- Nanoparticle-based slab
  - Porosity 85%
  - **Assuming 8 hr process**
  - Total cost: **$3.78/ft²**



Attractive cost but performance should match those of ambigel slabs

Lessons Learned

- Technical lessons
  - Our struggles
    - Ambient drying usually results in cracking of the monoliths
    - pore size tends increases with porosity
    - Pores larger than ~25 nm results in excessive haze for application
  - Some solutions
    - Omniphobic liquid substrates can reduce cracking
    - Low surface tension solvent exchange with TMCS makes the slabs porous, hydrophobic, and flexible
    - Slowing down the drying process keep the pore small and their size distribution narrow
- Management
  - Be flexible and creative while keeping your eyes on the prize
  - Make a plan with WBS, milestones, and go/no go decision
  - A diverse interdisciplinary team is key to success

Project Outputs

- Publications in press or submitted
  - 5 archival journal publications + 5 submitted/in preparation
  - 1 keynote at MRS meeting
- Patents filed and granted
  - Patent application PCT/US2019/39019, June 25, 2019
- Other T2M relevant activities
  - Cardinal IG
  - Nippon Sheet Glass

Project Next Steps

- ARPA-E Extension (July 2019-June 2021)
  - Scale up the process to 20” x 20” x 3 mm
  - Low-e coating deposition
  - Window integration and thermal testing
  - Develop plans for pilot plant
- Commercial strategy
  - Commercialize the technology through licensing to a glass manufacturer or fabricator
  - Commercial Readiness Level (CRL) = 3 going to 4
- Time to market: 5-8 years
  - Licensing to Piloting of full size production (+ 1-2 years)
  - Technology transfer (+ 1-3 years)
  - Commercialization (+2-3 years)

Bibliography

- U. Berardi, Applied Energy, 154 (2015) 603-615

QUESTIONS?

Prof. Laurent Pilon(PI)

pilon@seas.ucla.edu

Outline/Agenda

Time	Event
1:00 PM - 1:20 PM	**SHIELD Program Introduction and Retrospective** Dr. Marina Sofos, *ARPA-E*
1:20 PM – 2:50 PM	**SHIELD Team Project Recaps** 1. University of Colorado, Boulder: Prof. Ivan Smalyukh 2. Arizona State University: Dr. Shannon Poges 3. Palo Alto Research Center (PARC): Dr. Mahati Chintapalli 4. Aspen Aerogels: Dr. Wendell Rhine 5. University of California, Los Angeles: Prof. Laurent Pilon
2:50 PM – 3:00 PM	**SHIELD Program Commercialization Pathways** Patrick Finch, *ARPA-E/Booz Allen Hamilton*
3:00 PM – 3:15 PM	**Prospects for SHIELD aerogel technology for the windows market** Dr. George Gould, *Aspen Aerogels*
3:15 PM – 3:30 PM	**SHIELD Technology Durability Testing and Failure Assessment** Dr. Robert Tenent, *National Renewable Energy Laboratory*
3:30 PM – 4:00 PM	**Industry Perspective Presentations, Window product development, first markets and next steps for R&D** Dr. Kayla Natividad, *Pilkington* Dr. Keith Burrows, *Cardinal Glass*

Technology to Market Introduction

ARPA-E is unique among Federal research agencies in requiring a Tech-to-Market (T2M) component from its research teams

Scope

Provide strategic market insights necessary to create innovative, commercially-relevant programs

Manage

Manage project teams' T2M efforts through T2M plans and jointly developed milestones

Advise

Support project teams with skills & knowledge to align technology with market needs

Partner

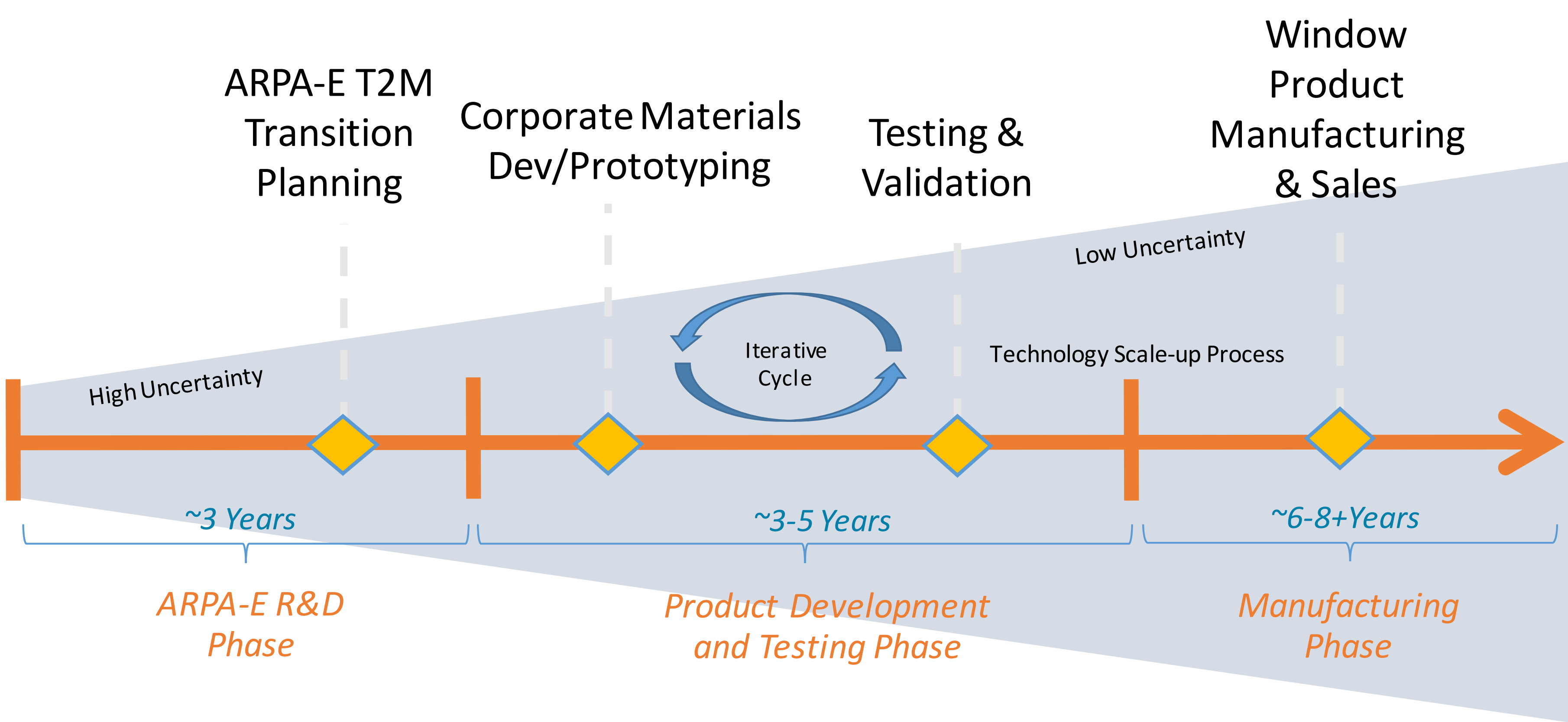
Engage third-party investors and partners to support technology development towards the market

Overview of T2M Learnings to Date

1. High level of market interest in more insulating and durable **IGUs**
   - Triple pane options are heavy and expensive
   - Vacuum glazing is reliant on maintaining their edge seal
2. To outperform current retrofit options, **lowering installation cost** is critical
   - Materials costs are generally not the primary cost driver
   - The initial SHIELD target may not have gone low enough!
3. **Durability** is key… but **validating** it even more so
   - These types of materials have long been equated with fragility
   - Accelerated aging is good, but more data is needed
4. The **scalability of manufacturing** is a significant challenge that is currently being addressed
   - Scaling while keeping yield high is critical to lowering costs
   - Minimizing drying step duration is critical to all processes
   - Can we move away from batch processes to a more continuous processes?

Technology to Market Timeline

Sample Technology Development Pathway



Our Speakers

- Corporate Materials Dev/Prototyping
  - Dr. George Gould, Aspen Aerogels

- Testing & Validation
  - Dr. Rob Tennant, National Renewable Energy Laboratory (NREL)

- Window Product Development
  - Dr. Kayla Natividad, Pilkington
  - Dr. Keith Burrows, Cardinal

2019 Buildings XIV International Conference

Workshop 8: DOE Building Envelope Research Projects on Fenestration and Grid Interaction

George Gould, Ph.D.
Chief Technology Officer
Aspen Aerogels, Inc.
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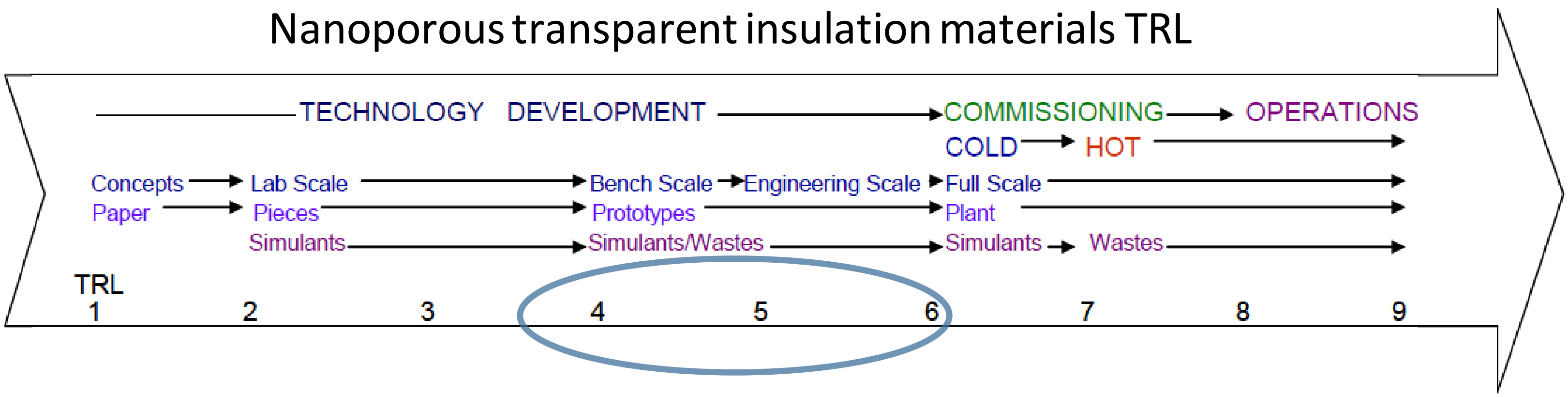
aspen aerogels

Nanomaterials Manufacturer Perspective: Next Steps for SHIELD Technologies

Observations -- General Technology Readiness Level



- Feasibility and fit for purpose – some are ready to begin scale up development
- Development discipline and investment is significant (formulation optimization, prototype machine design, process engineering)
- Risks are high on fit for purpose issues for nanoporous materials
  - Haze, color, clarity, geometric stability, cracking/damage

Next Steps for Advancing Commercialization

- Does the new technology meet the strategic objectives of the company?
  - *For us, the market size, adjacency to current offerings and innovation advantage as a fast mover are attractive*
- Is there a business case once market needs, adoption timeline, projected manufacturing costs and capital investment are considered?
  - *For our approach the risk level is perceived high and the required investment significant. ROI is low at current TRL*
- Are investors or partners willing to invest in the next level of development based on progress so far or is more basic/fundamental research needed?
  - A compelling business plan and robustly demonstrated manufacturing process at pilot scale are foundational not optional

More research needed

Suggested Knowledge Gaps to Address

- Basic Technology
  - Materials durability (especially with silicate aerogels)
  - Statistically relevant studies to assess variations in color, aging, haze, geometric stability
  - Design of experiments based deep dive into formulation and process variable interactions at lab scale, pilot scale
  - Low cost precursor integration into formulation
  - Handling, fabrication, packaging, application of product form factors
- Process Engineering Research
  - Fast cycle time approaches for low conversion costs
  - Scale effects on reproducibility, yield
  - Potential for automation
- Manufacturing Readiness
  - Regulatory, safety, supply chain partners, site
- Cost Modeling
  - Detailed unit operation modeling for energy usage, capacity, yield

Further Considerations

My perspective: There are solid business prospects for a fit for purpose insulating product in window applications but more research is needed. Your approach may require other considerations.

- Some prospective products are being prototyped with flammable organic solvents as part of the manufacturing process
  - Methanol is a HAP in many states and tightly regulated
  - Methanol is highly toxic
  - Ethanol requires special permits to use/store/ship
  - Flammable solvents at scale need special high hazard area rated equipment and emissions control equipment – understand fire hazards
- Do your sponsors/investors understand the magnitude required to get to commercialization? Aerogel materials - $10M+
- Are you ready to advance from lab to pilot scale?
  - Timelines and budgets are at risk when you advance too quickly
  - Detailed development needs a relatively narrow starting point
  - Make sure your plan is sustainable and that your product design is fit for purpose

Workshop 8: DOE Building Envelope Research Projects on Fenestration and Grid Interaction

Robert C. Tenent, Ph.D.
National Renewable Energy Laboratory
robert.tenent@nrel.gov

NREL
Transforming ENERGY

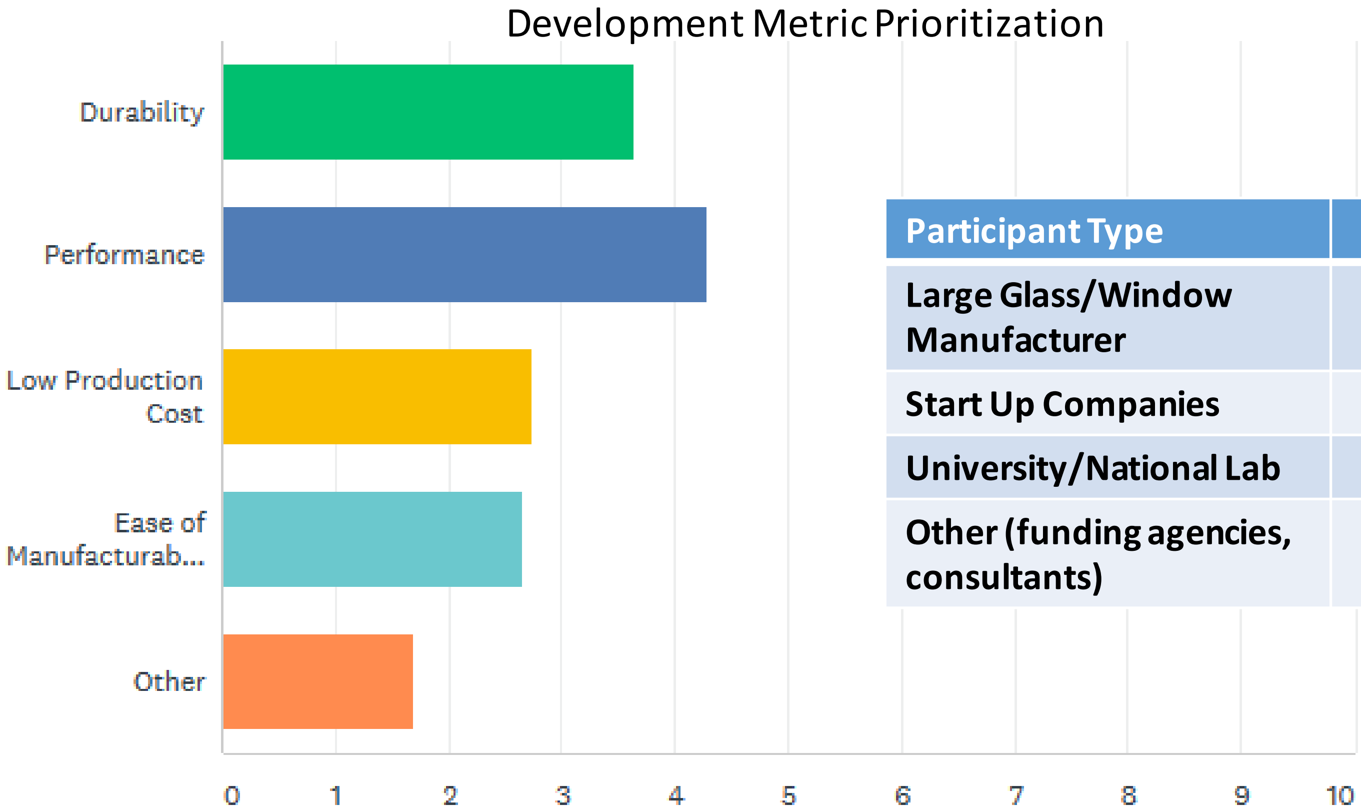
SHIELD Technology Durability Testing and Failure Assessment

Learning Objectives

- Discussion of relative importance of durability assessment in early stage fenestration technology development
- Identification of areas of importance for durability assessment of aerogel fenestration
- Discussion of how aerogel fenestration durability may be evaluated including current and planned research
- Discussion of relevant standards and ratings bodies for fenestration technologies

What do potential partners want?

Ranking the importance of four factors to the evaluation of an emerging fenestration technology



Participant Type	% of attendees
Large Glass/Window Manufacturer	32
Start Up Companies	21
University/National Lab	32
Other (funding agencies, consultants)	15

Most common "other" metric was aesthetics

Importance of Durability Demonstration

"Some one who approaches a glass company, should come with samples that have already been through durability testing, before they bring it to the glass company. They need to be capable of showing appearance and durability are good"

"IG elephant in the room is durability, windows are supposed to last forever, durability is huge. One failure and the consumer loses confidence."

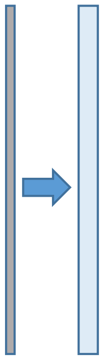
"Durability matters because you want it to last or customer will hate you for it"

What Factors May Be Most Important?

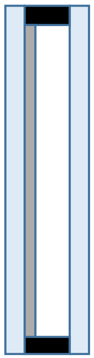
- Physical Contact
- Thermal Stresses
- Breakage
- Chemical Attack
- Mechanical Stresses
- Safety
- Solar/UV
- Chemical Release

Durability Assessment: Integration Matters

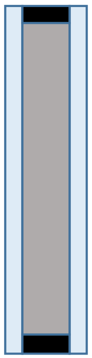
Example Integration Strategies



Applied Film



Applied Film
Interior Surface



Cavity Fill

- Low cost, simple installation
- Environmental exposure risks HIGH

- Increased cost
- Limited exposure risk
- Similar to VIG hybrid

- Increased cost
- Limited exposure risk
- Potential issues with mechanical stress

Current Durability Assessments

IGU/Window:

ASTM E2188/2189/2190 – Edge Seal Durability

North American Fenestration Standard

- Structural Strength
- Water Penetration Resistance
- Air Leakage
- Operating Force (optional)
- Forced-Entry Resistance (optional)

Window Film:

ASTM D882 – Physical Properties

ASTM D1044-D – Abrasion Resistance

ASTM E84 – Flammability

ASTM D1929 – Flame Ignition

Aerogel Durability Research

Simulated solar exposure and elevated temperature testing

- Monolithic aerogels
- IGU “encapsulated”

Conditions:
1 sun equivalent –
AM 1.5 solar spectrum matched Xe arc lamps
60 °C, < 60% RH in air

Differential thermal stress

- Planned

Temperatures 100 °C to -50 °C
Relative humidity 5% to 95%

Combined Accelerated Stress Testing

Factors applied cyclically

Light (with partial shading)
Temperature
Humidity (uncondensed)
Rain
Mechanical stress

- *Capability to apply all stress factors*
- *Programmatic control*
- *Database for*
  - *test parameters*
  - *run steps*
  - *module (T, I-V, P)*
  - *chamber (T, RH)*

Example: Rain and damp heat stage

- 40°C Rain (pulsed), 40°C chamber, >95% RH (dark)
  Pressure bars (pulsed, simulation of wind (or snow load). Pressure scaled for sample sizes through modeling and simulation)

Relevant Standards and Ratings Bodies

- National Fenestration Ratings Council (NFRC)
- Fenestration and Glazing Industry Alliance (FIGA)
  - Formerly AAMA and IGMA
- Insulating Glass Certification Council (IGCC)
- Window and Door Manufacturer's Association (WDMA)

Questions

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National Renewable Energy Laboratory
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Workshop 8: DOE Building Envelope Research Projects on Fenestration and Grid Interaction

Dr. Kayla Natividad
Pilkington North America

Who is NSG Pilkington North America?

Raw Material Extraction

Float Glass Process

- Pyrolitic Coated

Glass Fabrication

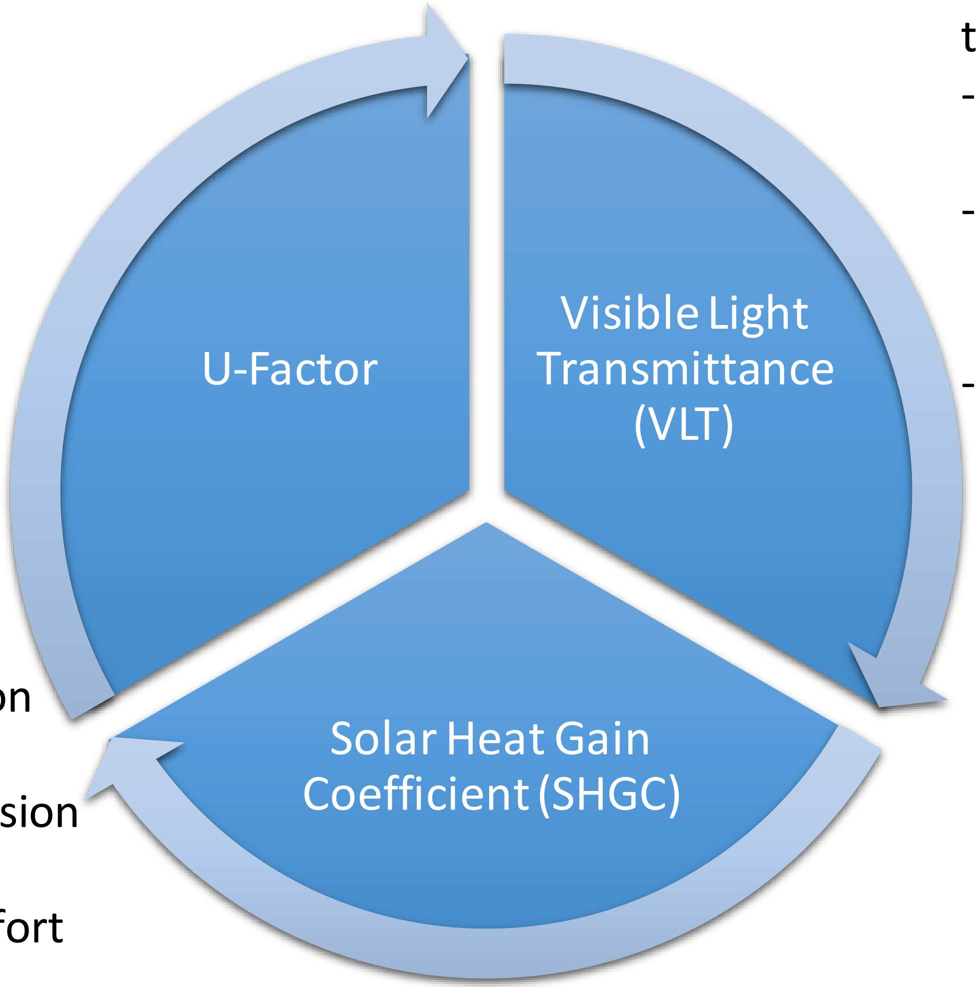
- Heat Treated
- Laminated
- Sputter Coated
- IGU
- Etc.

Distribution

Construction Installation

- Our customers include fabricators, architects, engineers, building owners, building occupants.

Customer Feedback



High visible light transmission:
- Improve quality views
- Reduce need for artificial lighting
- Improve occupant health and productivity

Low U-Factor
- Better window insulation

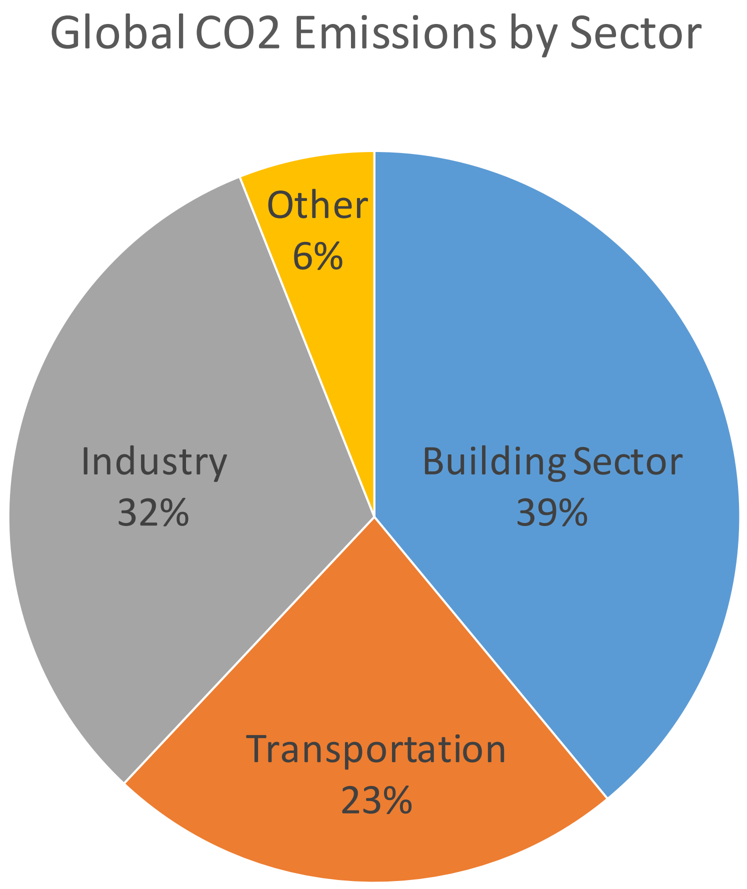
Low SHGC
- less solar heat transmission

Both:
- Improve occupant comfort
- Reduce HVAC load requirements

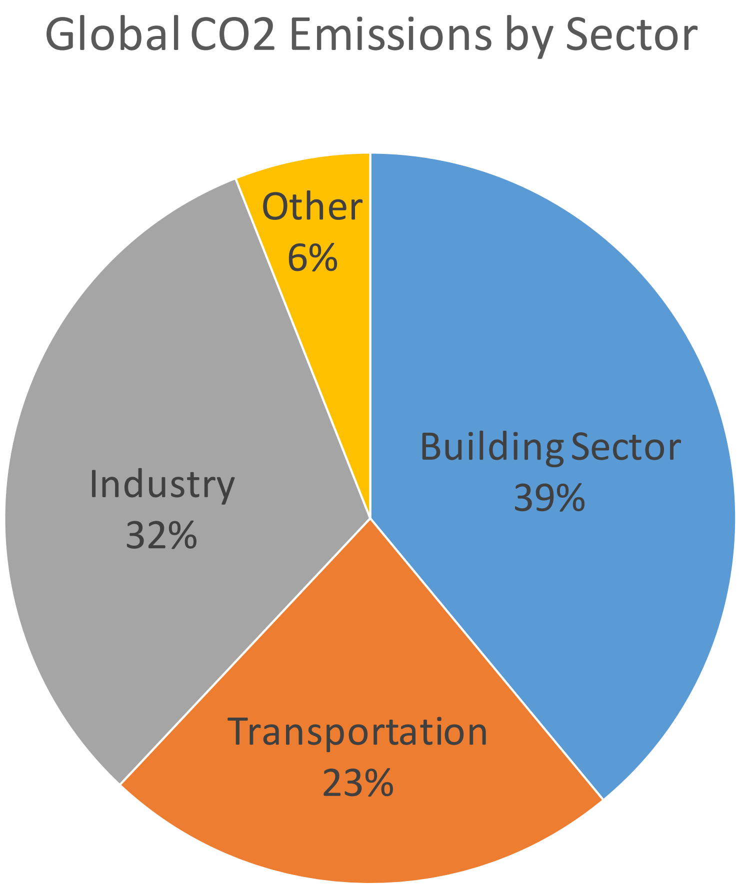
Building Sector Drivers

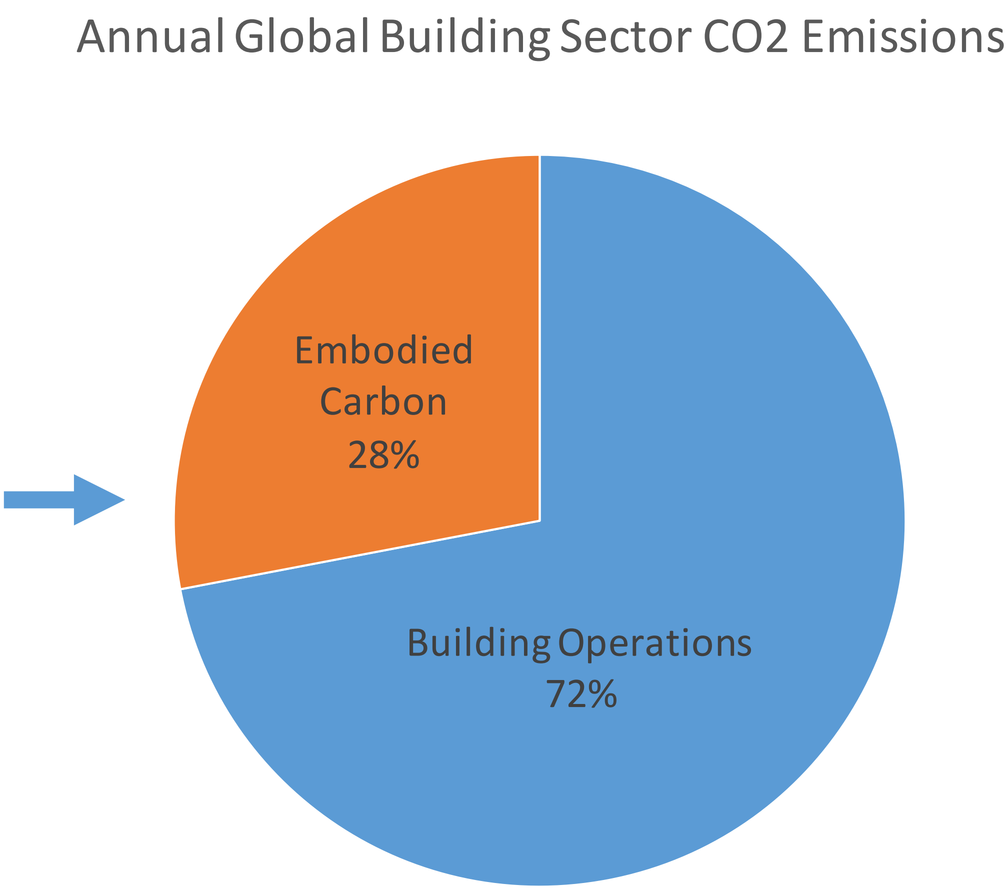
Strong push for net zero and sustainable buildings through:

- City Codes
- State Codes
- Voluntary Design Codes
  - LEED
  - WELL
  - Passive House
  - Living Building



Building Sector Today





Building Sector Tomorrow

- Energy codes for new construction becoming more stringent
  - ~2030 Targets focused on renewable energy, emission reduction, and building energy performance
- Since 2/3 of the building area that exists today will still exist in 2050 emphasis should also be on reduction in energy consumption and emissions of existing building stock
  - Existing energy codes don't always apply to existing buildings
    - NYC and Seattle require buildings undergoing major renovations to come close to energy performance requirements for new buildings UNLESS it is detrimental to building
  - Movement towards improved fenestration through: prescriptive code, trade-off, benchmarking

Glazing Technology

New technology to address these concerns are:

- Thin Triple IGU (light-weight – fits in double IGU profile)
- Vacuum Insulating Glass (thin profile – easy high performance monolithic replacement)
- Dynamic Glazing (added functionality)
- Transparent BIPV (added functionality)

Workshop 8: DOE Building Envelope Research Projects on Fenestration and Grid Interaction

Keith Burrows
Cardinal Glass Industries
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CARDINAL
Glass Industries

Architectural Glass Needs and Opportunities

Improving Window Performance

The thermal performance of architectural glass is measured in two primary ways:

Metric	Description	Target	Ongoing Needs
U-factor	Heat loss through window	Lower is better	scalable materials
SHGC	Solar heat gain through window	No single optimal value	dynamic materials

SHIELD (successfully) targeted improved U-factors, but a scaled solution is still required.

Existing products offer a range of static SHGC's that cover the market's needs, so the opportunity there is for dynamic SHGC materials (thermochromic, electrochromic, liquid crystal, etc) that respond to conditions.

Not Just Energy Performance

The decision to adopt a technology for architectural glass is not as simple as evaluating SHGC, U-factor and cost.

The industry is slowly moving towards a more integrated approach, so you will need to also consider:

- Occupant comfort, productivity, safety, and health.
- The life cycle of the product including embodied energy, operation, maintenance, and end-of-life.

Single Pane vs IGU

SHIELD aimed to improve the performance of single pane windows, but the best opportunity for your technologies is in IGU's (insulated glazing units).

Advantages of integration into an IGU

- Higher end of market = more willingness and ability to pay
- Higher volume market
- IGU provides encapsulation = protection from humidity, UV, scratching & abrasion, and chemical damage
- Partner with the largest and most technical participants in the supply chain (glass manufacturers, coaters, and IGU fabricators)

What I need to evaluate a new technology

- Performance & optical data. Bonus if 10 mm x 10 mm samples are available for our own in-house testing.
- Initial durability testing. Not critical that glass industry standard tests are used.
- Cost model & IP position
- <u>Evidence of Scalability (not scale)</u>
- But I don’t need any of the above to have a conversation—if you have an idea, reach out.